t No. FHWA-RD-78-137

FORMULATION OF GUIDELINES FOR LOCATING FREEWAY SENSORS

December 1979
Interim Report

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Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

FOREWORD

This report is part of a larger research effort, "Control Strategies in Response to Freeway Incidents." The overall study considers methods for alleviating congestion caused by capacity-reducing freeway incidents.

One component of the research (not documented in this report), develops and evaluates control strategies that can be used during freeway incidents. These strategies utilize data provided by electronic freeway sensors.

This particular report formulates the basis for guidelines and procedures to determine the optimum spacing and location of electronic sensors based on roadway geometry, funding constraints, and other parameters.

Copies of this report are being distributed to provide a minimum of two copies to each regional office, two copies to each division office, and three copies to each State highway agency. The division and State copies are being sent to the division office. Because of the nature of the report's contents, copies are also being sent to selected traffic engineers and chiefs of police. Additional copies for official use may be requested from Mr. Joseph W. Hess, Acting Chief, Traffic Systems Division, Federal Highway Administration, HRS-33, Washington, D. C. 20590. These requests will be filled while the supply lasts.

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Charles F. Scheffey
Director, Office of Research

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-78-137	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Formulation of Guidelines for Locating Freeway Sensors		5. Report Date December 1979
		6. Performing Organization Code
7. Author(s) H.M. Koble, G.M. Anderson, R.B. Goldblatt		8. Performing Organization Report No.
9. Performing Organization Name and Address ORINCON Corporation, 3366 N. Torrey Pines Court, La Jolla, CA 92037; KLD Associates, Inc., 300 Broadway, Huntington Station NY 11746		10. Work Unit No. (TRAIS) 31C3-522
		11. Contract or Grant No. DOT-FH-11-9367
12. Sponsoring Agency Name and Address U.S. Department of Transportation, Federal Highway Administration, Offices of Research and Development, Washington, D.C. 20590		13. Type of Report and Period Covered Interim Report November 1977 to July 1978
		14. Sponsoring Agency Code T-0339

15. Supplementary Notes

FHWA Contract Manager: S.C. Tignor (HRS-33)

16. Abstract

Guidelines and procedures are developed for specifying the location and spacing of sensors needed and used by algorithms which detect freeway incidents. The sensor placement problem is considered for each of the following geometric features: freeways containing only level, tangential sections of roadway with on and off ramps; freeways containing weaving areas of between 1000 and 3000 feet (305 and 914 M); freeway segments containing a change in the number of lanes; and freeway segments with a change in the alignment. The guidelines and procedures permit the user to determine the optimum spacing of sensor stations given the: roadway geometry, the funding available for sensor installation, and the requirements for incident detection algorithm performance. Major emphasis is placed upon assessing the tradeoffs between cost and effectiveness of a variety of candidate sensor configurations.

17. Key Words Incident detection, sensor placement, freeway surveillance, ramp control, traffic simulation, cost effectiveness		18. Distribution Statement No restriction. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 136	22. Price

Form DOT F 1700.7 (8-72)

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

TABLE OF CONTENTS (CONT'D)

LIST OF FIGURES

LIST OF FIGURES (CONT'D)

LIST OF FIGURES (CONT'D)

LIST OF TABLES

LIST OF TABLES (CONT'D)

TABLE PAGE

CHAPTER 1

INTRODUCTION

This is a report pertaining to the overall research study "Control Strategies in Response to Freeway Incidents". The study is concerned with the problem of alleviating the congestion and other debilitating effects attendant with capacity-reducing freeway incidents by controlling the rate at which vehicles are allowed to enter the freeway proper at on-ramp locations. It has two major research components. One of these is the development and evaluation, through simulation techniques, of new strategies (computer algorithms) for ramp control. Such strategies would be implemented with an automated surveillance and control system once an incident had been detected on the freeway. Guidelines and procedures for implementation will be considered and reported on later in the overall study. The second research area pertains to the development of guidelines for locating freeway sensors, a subject which this report specifically addresses.

A key ingredient to the successful operation of any incident-responsive control strategy is valid and realistic data about the traffic flow and condition. Most operational strategies only require information about the congestion produced by the incident and thus use the measurement data directly. However, such strategies tend to produce a sluggish response to the congestion in freeway segments upstream of the immediate incident vicinity. This can be a very undesirable response in severe incident situations. As a consequence, this study is considering some alternative strategies which also require incident-specific information such as the capacity at the incident site, the location of the incident, and the time of occurrence and clearance. Such strategies require preprocessing of the measurement data by an incident detection algorithm designed to determine if an incident has, in fact, occurred.

The measures or samples of the traffic conditions required by these incident detection algorithms are provided by a system of sensors located in the freeway lanes. The configuration of these sensors can have a major effect upon the performance of the detection algorithms. Consequently, research was performed to quantify this effect and to develop recommendations for effective sensor configurations.

Unfortunately, very efficient incident detection may require a very expensive system of sensors, exceeding the operating budget. A key issue therefore involved quantitative investigation of how detectorization impacts implementation costs. This report will discuss the findings and provide basic guidelines for locating freeway sensors.

1.1 STATEMENT OF WORK

In more specific terms, the objectives of the investigation were to develop guidelines and procedures for specifying the location and spacing of sensors needed and used by algorithms designed to detect freeway incidents. The previous work in these areas (1, 2) has been confined to straight sections of freeway containing no on and off ramps. Consequently, in this effort, consideration was given to a wider range of geometric features.

1. Mainline one-direction freeway sections five miles (eight kilometers) in length, having on and off ramps every 3/4 mile (1.2 kilometers). Both three and four lane one-directional freeways were considered.
2. Weaving areas of 1000, 2000, and 3000 feet (305, 610 and 915 M) in length.
3. Lane drops and additions.
4. Bottlenecks created by changes in vertical and horizontal alignment.

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[1] Mosami Sakasita and Adolf D. May, "Development and Evaluation of Incident Detection Algorithms for Electronic Detector Systems on Freeways, "Report DOT-TST-75-94 (NTIS-PB #243-385), August 1974.

[2] Conrad L. Dudek and Carrol J. Messer, "Incident Detection on Urban Freeways," Transportation Research Record 495, Transportation Research Board, Washington, D.C., 1974.

The guidelines and procedures were designed to permit the user to determine the optimum spacing given the:

1. Roadway geometric features.
2. Performance requirements of the incident detection algorithm.
3. Funding available for sensor installation.

Major emphasis was placed on developing cost-effective procedures for specifying sensor spacing.

The results for each geometric feature were based upon extensive simulation of traffic behavior under both incident and non-incident conditions using the microscopic, stochastic model INTRAS (3). Each simulation resulted in a history of the time and duration of actuation of vehicles passing over the deployed sensors. The simulated data was processed by two representative incident detection algorithms: the Modified California algorithm described by Sakasita (4) and Algorithm 7 described by Payne (5).

A total of four candidate sensor station spacings were considered: 500, 1000, 2500, and 5000 feet (152, 305, 762, and 1524 M). Consideration was also given to two different lane configurations at each station: full (sensors in each lane) and partial (a sensor in the center lane of three lane one-directional freeways; sensors in lanes 2 and 4 of four lane one-directional freeways). Two station offsets were investigated: one for incidents occurring midway between adjacent stations and one for incidents immediately upstream of a sensor station.

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[3] D.A. Wicks, R.B. Goldblatt, et al., "Development and Testing of INTRAS, a Microscopic Freeway Simulation Model," Volumes 1-4, FHWA Final Report, August 1977.

[4] Mosami Sakasita and Adolf D. May, Ibid.

[5] H.J. Payne, et al., "Development and Testing of Incident Detection Algorithms, Volume 2: Research Methodology and Detailed Results," Report FHWA-RD-76-20, April 1976.

1.2 ORGANIZATION OF THE REPORT

The first phase of the research effort involved the design and implementation of an experimental program to collect and analyze the required sensor data. In Chapter 2, the key elements of the experimental program design are defined and discussed in quantitative fashion.

In Chapter 3, the dependence of incident detection algorithm performance upon the particular sensor configuration providing the input data is quantified. Two effectiveness measures, the detection ratio and the average time to detect (assuming detection occurs), are employed. Consideration is also given to the matter of false alarms. Results are presented for each of the four geometric features. In general, the evaluation indicates that freeway sensors should be separated by a distance of between 1000 and 2500 feet (305 and 762 M) to achieve the most effective algorithm performance. Decreasing the spacing to 500 feet (152 M) increases the false alarm rate with little improvement in detection ratio and detection time. Both the full and partial sensor configurations result in comparable algorithm performance.

More definitive information is obtained by introducing cost considerations into the analysis. This is the subject of Chapter 4. Therein, a sensor configuration costing procedure, which should be applicable regardless of the user's locality, is presented. The procedure is designed to be independent of the variables that affect cost such as inflation rate, discount rate, and differences in the price charged by various vendors of equipment. A series of graphs are presented showing the tradeoffs between incident detection algorithm performance and costs for each candidate sensor configuration under consideration. Instruction on their usage is provided. These graphs provide the primary data which will enable the user to determine optimum sensor spacing given: the geometric features of the roadway, the available budget, and his own requirements for incident detection algorithm performance. When cost factors are considered, the partial sensor configurations are preferred to the full configurations.

Concluding this report, Chapter 5 summarizes the guidelines for the cost-effective placement of sensors. General recommendations along with specific comments apropos to each geometric feature are provided.

CHAPTER 2

PROCEDURES FOR COLLECTING AND ANALYZING SENSOR DATA

The first phase of this study involved the design and implementation of an experimental program to collect and analyze the data required to evaluate the effect of sensor placement upon the performance of an incident detection algorithm. A computer simulation model of freeway traffic behavior and surveillance system operation called INTRAS (INtegrated TRAffic Simulation) was utilized for this purpose. This model is microscopic in nature, i.e. it simulates the movements of individual vehicles. A comprehensive description of the capabilities and limitations of INTRAS may be found in (1).

In this chapter, the key elements of the experimental program design will be identified and discussed in quantitative fashion. To orient the reader, the presentation will begin with a general overview.

2.1 AN OVERVIEW OF THE EXPERIMENTAL PROGRAM

A block diagram of the experimental program design, showing the flow of information through the INTRAS model, is presented in Figure 1.

Sensor Data Collection

In general, the main input parameters which must be specified to execute a given simulation run fall into one of four categories:

- the physical configuration of the freeway facility,
- the traffic demand that exists on the facility at both the upstream boundary and the ramps,
- the incident scenario (location, duration, lane blockage specification, etc.),

  and
- the surveillance sensor configuration which will be deployed to collect information on the traffic conditions.

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[1] D. A. Wicks, R. B. Goldblatt, et al., Ibid.

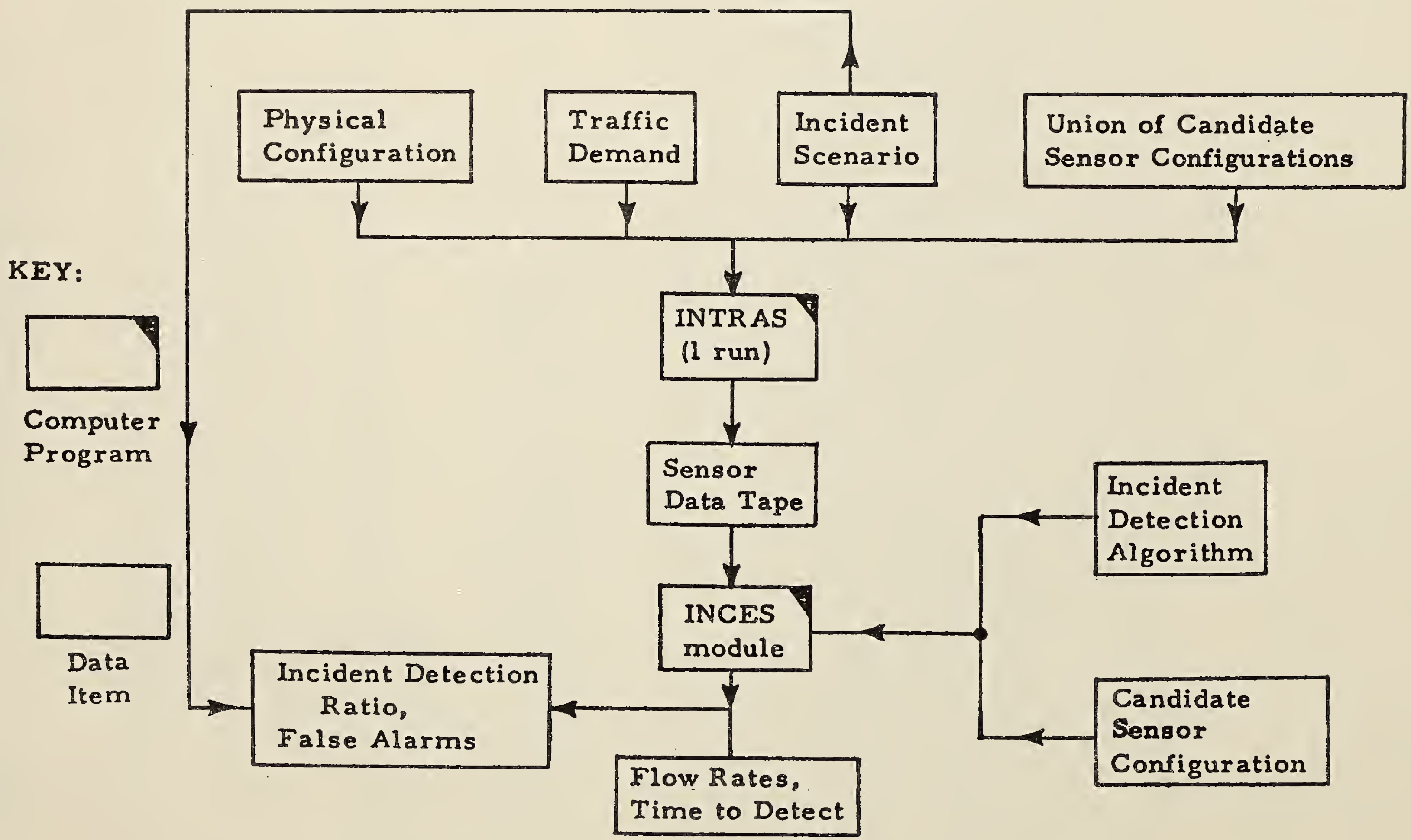


FIGURE 1 INFORMATION FLOW FOR THE EXPERIMENTAL PROGRAM

As output, the INTRAS model will produce a simulated history of the time and duration of actuation of individual vehicles passing over the deployed sensors. This output may be stored, as was the case for this study, on magnetic tape for subsequent processing and analysis.

Geometric Features

The specific series of simulation runs designed to study the problem of sensor placement was divided into four separate areas, each covering an important geometric feature of freeway design. These design features were: MAINLINE SECTIONS - freeway facilities which are composed only of level, tangential roadway sections; WEAVING SECTIONS - freeway facilities which contain weaving areas producing turbulent flow; LANE DROPS AND ADDITIONS - freeway facilities which contain a reduction or addition in the number of lanes; and ALIGNMENT SECTIONS - freeway facilities which contain a change in the horizontal or vertical alignment.

Candidate Sensor Configurations

To conserve funds, the sensor configuration deployed for all simulations involving a particular geometric type represented the union of all candidate configurations under investigation. These candidate configurations were differentiated by three factors: (1) the number of instrumented lanes at a given station, (2) the spacing between the stations, and (3) the station offset. Figure 2 provides a visual summary of the candidate sensor configurations.

With regard to the first factor, consideration was given to a full station instrumentation (sensors in all lanes) and a partial station instrumentation (sensor in the center lane of a three lane one-directional freeway, sensors in lanes 2 and 4 of a four lane one-directional freeway).

A total of four station spacings were considered in this study: 500, 1000, 2500, and 5000 feet (152, 305, 762, and 1524 M, respectively).

Two offsets were investigated; one for incidents occurring midway between adjacent stations and one for incidents occurring immediately upstream of a sensor station.

Simulation Scenario

Each execution of the INTRAS model involved ten minutes to fill the facility with vehicles (no data was gathered during this time period),

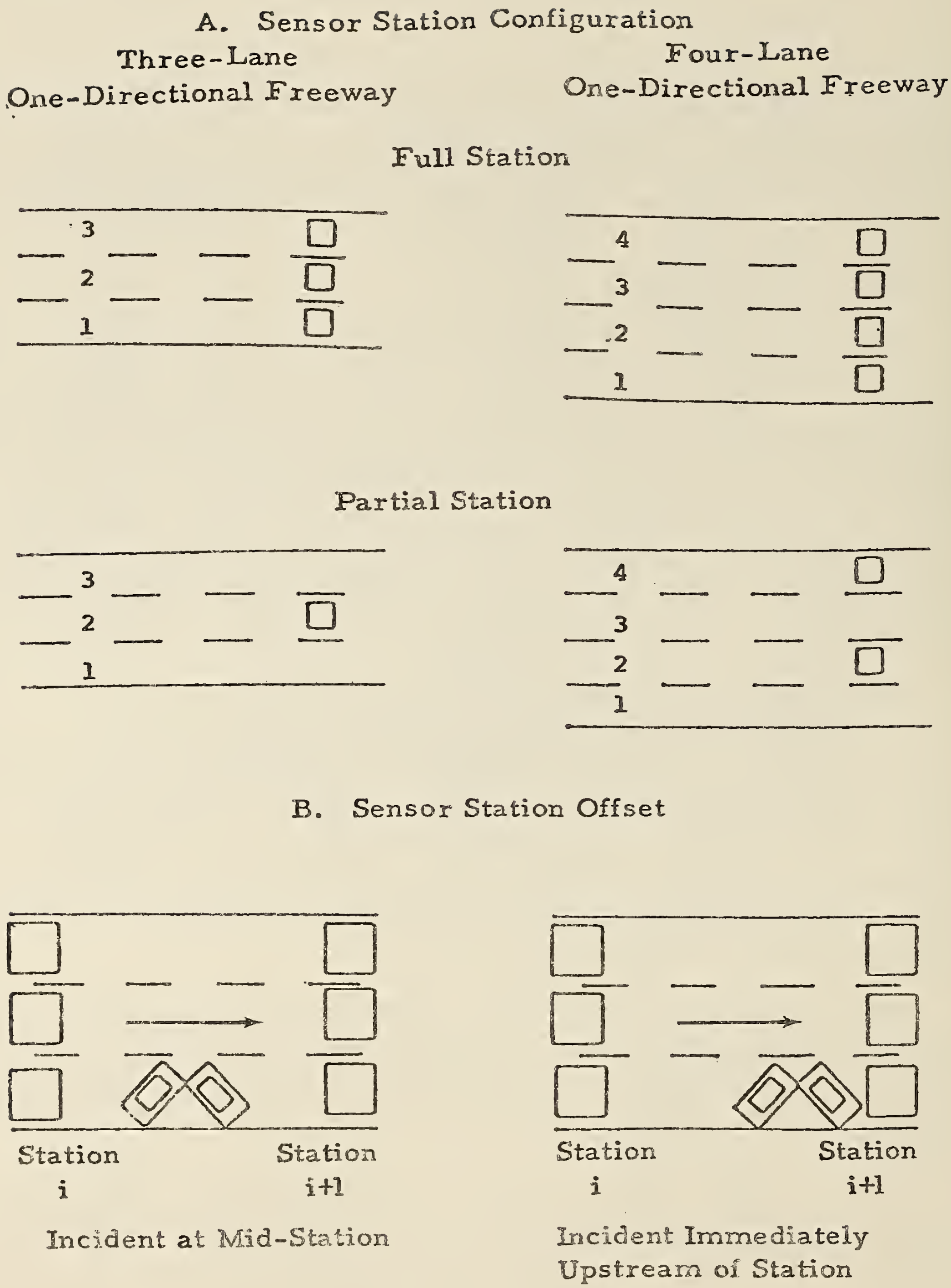


FIGURE 2 CANDIDATE SENSOR CONFIGURATIONS

five minutes under incident free conditions, fifteen minutes under incident conditions, and an additional five minutes once the lane blockage had been removed.

Additional information regarding the physical configuration, the traffic demand, the incident location and lane blockage specification, and the deployed union of candidate sensor configurations may be found in Section 2.2.

Data Processing and Analysis

The INCident Detection and EStimation (INCES) module of the INTRAS model was used to perform off-line processing and analysis of the sensor actuation data produced by each simulation run.

Flow Rate Information

Information concerning traffic conditions before, during, and after the incident was obtained by estimating three critical flow rates:

- arrival demand (vehicles per hour arriving at the incident site) prior to incident initiation (average of five one-minute periods),
- discharge capacity (vehicles per hour) at the incident site during lane blockage (average of fifteen one-minute periods), and
- get-away flow (vehicles per hour leaving the incident site) after the blockage is cleared (average of five one-minute periods).

Each of these flow rates was measured across all lanes in one direction of the freeway facility.

Incident Detection Algorithms and Measure of Effectiveness

In addition, the data associated with each candidate sensor configuration described previously was extracted and input to each of two incident detection algorithms which have been coded as part of the INCES module. The algorithms used for the study were the Modified California Algorithm (1), and Payne's Algorithm No. 7 (2).

[1] M. Sakasita and A. D. May, Ibid.

[2] H. J. Payne, E. D. Helfenbein and H. C. Knobel, Ibid.

This data processing effort directly produced the time, in minutes, between initiation of an incident and its detection. This will be referred to as the time to detect. By comparing the output of the incident detection algorithm with the actual simulated scenarios, information was also obtained on the percentage of real incidents detected (incident detection ratio) and the percentage of false alarms (false alarm rate).

These three parameters served as the measures of incident detection algorithm effectiveness used in this study. Elaboration on their definition as well as incident detection algorithm logic will be given in Section 2.3.

2.2 DESIGN OF THE INTRAS SIMULATION EXPERIMENTAL PROGRAM

Further details will now be given regarding the series of simulation runs which were performed on the INTRAS model to collect the required sensor actuation data. Each of the following sub-sections is devoted to one of the four geometric features of freeway design discussed earlier.

Mainline Freeway Sections

The purpose of this set of runs was to provide data needed to determine optimum sensor placement on tangent freeway sections with no grades. In addition, a number of runs were designed to specifically assess the effects of on and off ramps upon sensor placement. Two different physical configurations were used to accomplish these goals.

The mainline network consisted of approximately five miles (8 km) of freeway section. Both six and eight lane freeways (three and four lanes, respectively, in each direction) were considered. On and off ramps were situated at 3/4 mile (1.2 km) intervals. Figure 3 presents the freeway facility (only three one-directional lanes for the six lane freeway are displayed).

Prominent in this figure is the universal sensor set designed for this geometric feature. This set made it possible to study all candidate sensor configurations discussed previously without having to perform a separate simulation for each. A total of 32 stations, with 96 sensors for the three lane one-directional freeway and 128 sensors for the four lane case, were included (denoted as A-FF). Table 1 presents the list of stations used for each station spacing and offset. For example, with 2500 foot (762 M) spacing and the incident located midway between two sensor stations, stations H, K, P, Z and EE, as shown in Figure 3, were used.

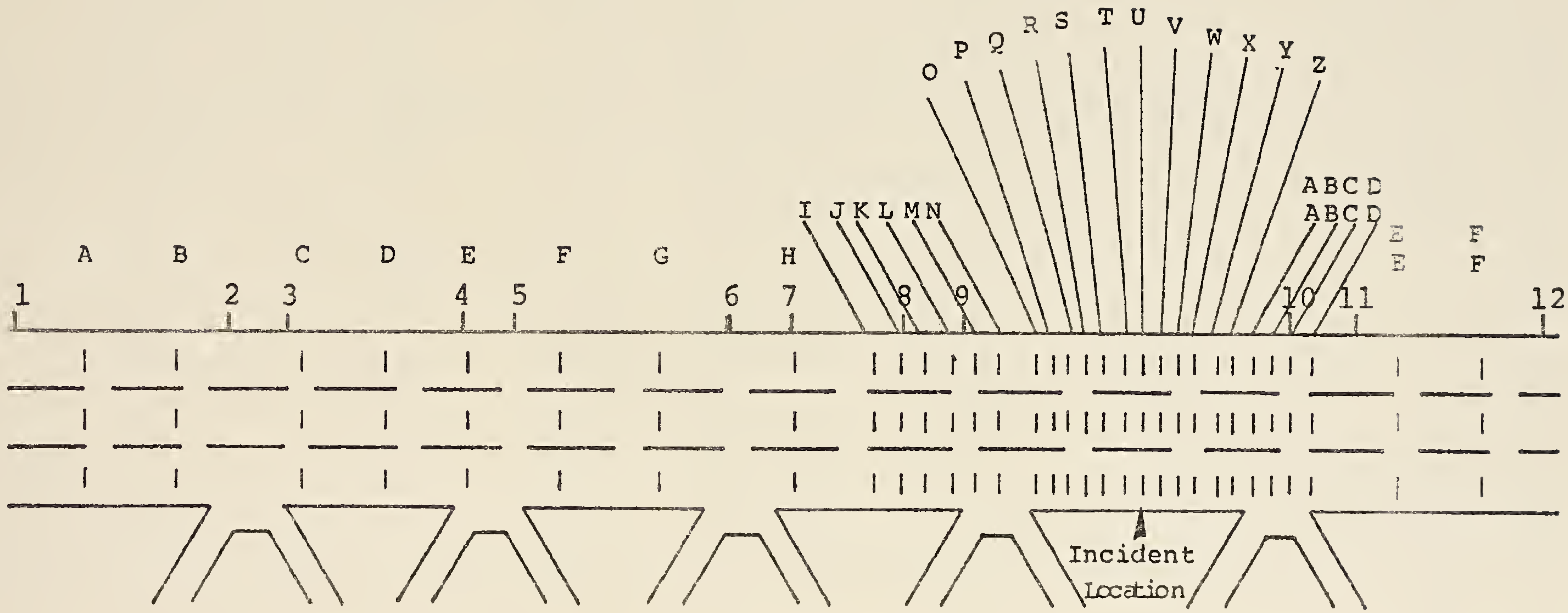


FIGURE 3 MAINLINE NETWORK AND SENSOR SET

TABLE 1: MAINLINE UNIVERSAL SENSOR SET

Station Spacing	Incident Midway between Two Sensor Stations	Incident Immediately Upstream of a Sensor Station
	K	J
	L	K
	M	L
	N	M
	P	N
	R	O
500 ft.	T	Q
(152 M)	V	S
	X	U
	Z	W
	BB	Y
	CC	AA
	DD	BB
		CC
		DD
	K	I
	M	J
	O	L
1000 ft.	S	N
(305 M)	W	Q
	AA	U
	DD	Y
		CC
	H	I
	K	M
2500 ft.	P	U
(762 M)	Z	CC
	EE	EE
	D	F
5000 ft.	H	I
(1524 M)	M	U
	CC	EE

Four types of incidents were simulated: 1) left lane blocked, 2) right lane blocked, 3) two left lanes blocked, and 4) two right lanes blocked. In addition to simulating lane blockages, capacity was reduced in the unblocked lanes in the vicinity of the incident. This was designed to simulate the effect of "rubber-necking".

A total of 32 INTRAS runs were made. The data matrix for these runs is presented in Table 2. In addition, two runs were made with no incident present. The purpose was to provide data which could be used to assess the occurrence of false alarms generated by the incident detection algorithms. In each case, a rapidly peaking volume was simulated. The time history of these volumes for this investigation of false alarm rates is shown in Table 3.

Part way through the simulation activity, it was decided to modify the design to incorporate a study on the effect of on and off ramps on sensor placement. A 1000 foot (305 M) station spacing was chosen to be the test configuration since it had yielded representative results during the first phase of activity.

The physical configurations used for the on and off ramp study are shown in Figure 4. Notice that, for each network, two separate station pairs were deployed; the variable being the location of the station upstream of the incident relative to the ramp location.

The data matrix for this set of runs is shown in Table 4. Freeway volumes were held constant at 4500 vehicles per hour. Two types of incidents were studied: blockage of the right lane and blockage of the two right lanes.

Weaving Sections

The reason for studying a weaving section was to see what effects the normal turbulent flows through such a section have on the selection of sensor placement. To accomplish this end, the eight lane network (four lanes in each direction), shown in Figure 5, was used. The network represents a major merge-diverge point with its implied flow turbulence due to the large amount of lane changing. The length of the weaving section (between nodes 3 and 5) varied between 1000 feet (305 M) and 3000 feet (914 M). Included in Figure 5 is the universal sensor set for this particular series of runs. Table 5 presents the sensor stations used for each combination of offset and spacing. The five types of incidents simulated were 1) right lane blockage, 2) left lane blockage, 3) center lane blockage, 4) two left lanes blocked, and 5) two right lanes blocked. In all cases, the incident was located at

TABLE 2 MAINLINE DATA MATRIX

Runs	Number of One-Directional Lanes	Volume (veh/hr/lane)	Incident
1-4	3	1000, 1300, 1500 1800	Left lane blocked
5-8	4	1000, 1300, 1500 1800	Left lane blocked
9-12	3	1000, 1300, 1500 1800	Right lane blocked
13-16	4	1000, 1300, 1500 1800	Right lane blocked
17-20	3	1000, 1300, 1500 1800	Two left lanes blocked
21-24	4	1000, 1300, 1500 1800	Two left lanes blocked
25-28	3	1000, 1300, 1500 1800	Two right lanes blocked
29-32	4	1000, 1300, 1500 1800	Two right lanes blocked
33	3	Variable	None
34	4	Variable	None

the midway point of the weaving section. Table 6 presents the data matrix for the weaving section runs.

Lane Drops and Additions

This set of runs was designed to produce data needed to study sensor placement on facilities containing a change in the number of lanes. The two cases studied were (1) the addition of a lane at an on ramp, at which point a three lane one-directional freeway expands to four lanes and (2) the loss of a lane at an off ramp, at which point a four lane one-

TABLE 3 TIME VARIATION OF VOLUME LEVELS FOR FALSE ALARM INVESTIGATION

Time (Minutes)	Volume (veh/hr/lane)
0-3	1000
4-6	1200
7-9	1400
10-12	1600
13-15	1800
16-18	1800
19-21	1600
22-24	1400
25-27	1200
27-30	1000

directional freeway becomes three lanes. Figure 6 presents the network simulated for these cases. It should be noted that the universal sensor set is designed to remain unchanged relative to the incident location. It can be viewed as an overlay to be impressed upon the roadway and can be shifted as the incident location is shifted. For this reason, the weaving section sensor table (Table 5) is also valid for this series of runs. The ten incident types considered for these two cases were:

Lane Additions

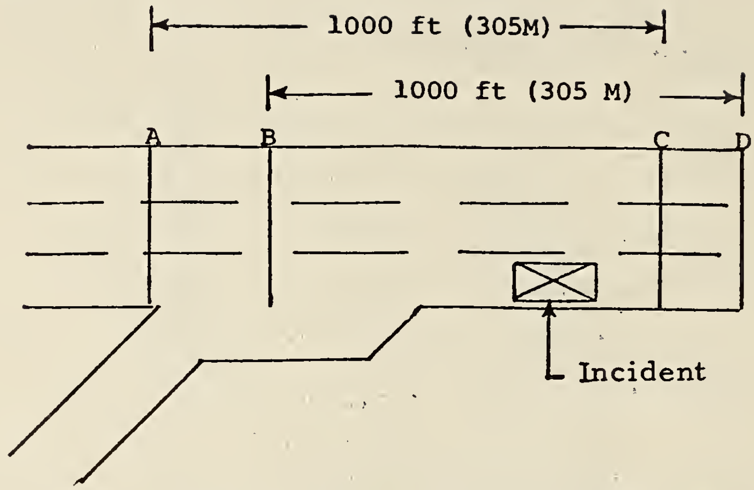
- right lane blocked upstream of the lane addition
- right lane blocked downstream of the lane addition
- two right lanes blocked upstream
- two right lanes blocked downstream

Lane Drops

- right lane blocked upstream of the lane drop
- right lane blocked downstream of the lane drop
- median lane blocked at the taper
- two right lanes blocked upstream
- two right lanes blocked downstream
- two lanes blocked at the taper.

Table 7 presents the data matrix for this set of runs.

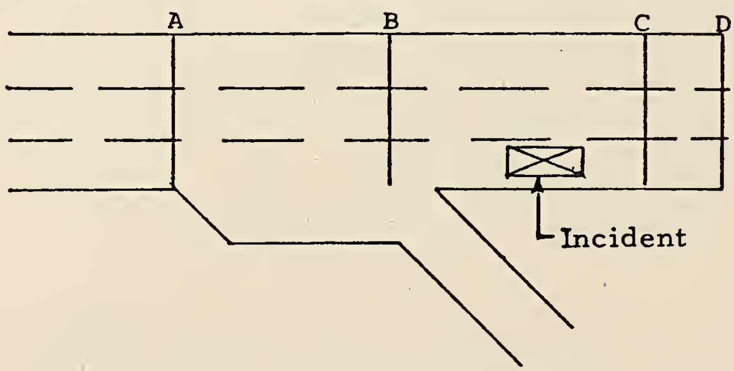
ON-RAMP NETWORK



Sensor Station Upstream of On-Ramp, Use Stations A and C

Sensor Station Downstream of On-Ramp, Use Stations B and D

OFF-RAMP NETWORK



Sensor Station Upstream of Off-Ramp, Use Stations A and C

Sensor Station Downstream of Off-Ramp, Use Stations B and D

FIGURE 4 RAMP POSITION NETWORK

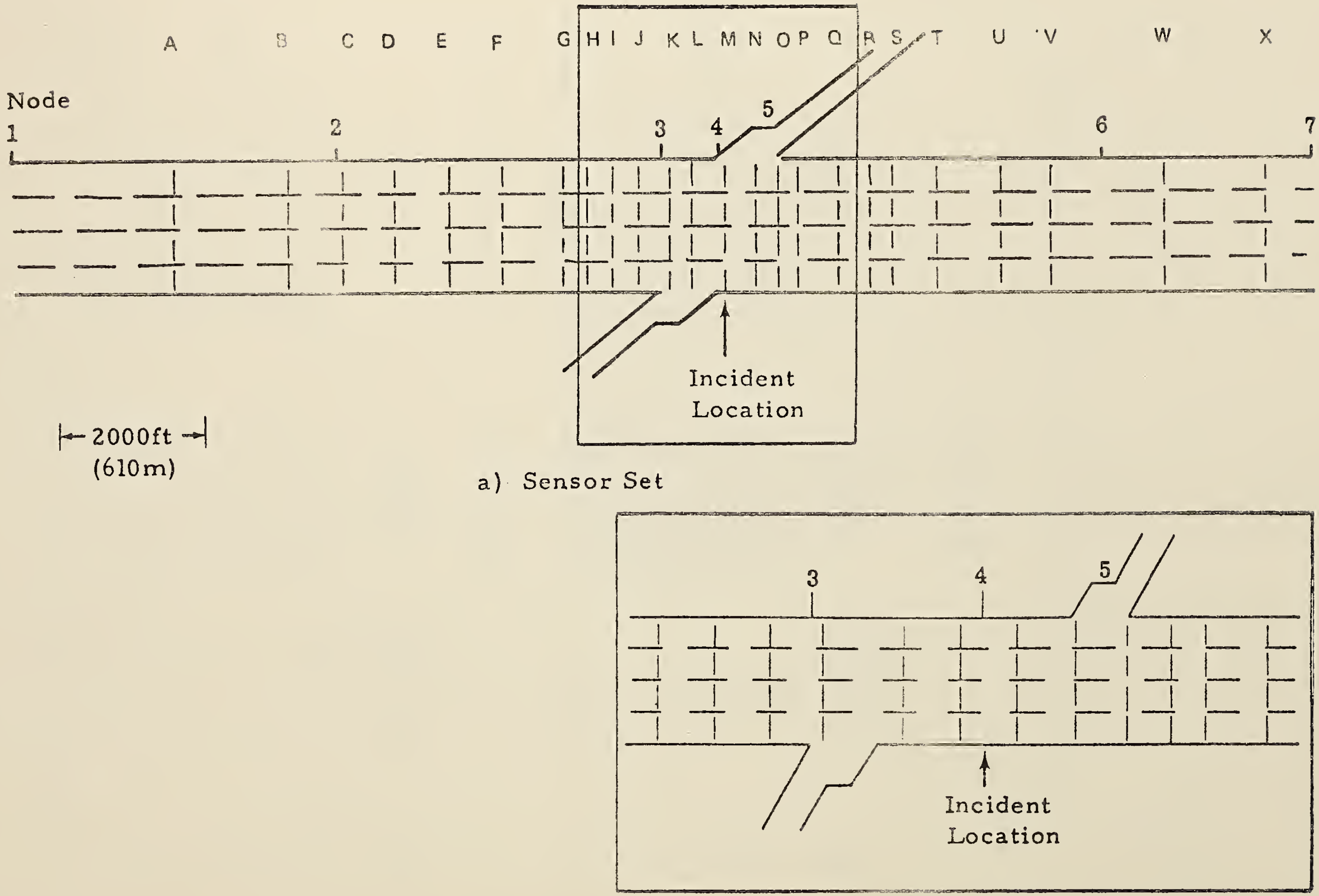
TABLE 4 ON-, OFF-RAMP STUDY DATA MATRIX

On-Ramps

Run	Ramp Volume (veh/hr)	Ramp Position	Incident
1	500	Upstream	Right lane blocked
2	500	Downstream	Right lane blocked
3	500	Upstream	Two right lanes blocked
4	500	Downstream	Two right lanes blocked
5	1000	Upstream	Right lane blocked
6	1000	Downstream	Right lane blocked
7	1000	Upstream	Two right lanes blocked
8	1000	Downstream	Two right lanes blocked

Off-Ramps

Run	Turn Percentage	Ramp Position	Incident
9	5	Upstream	Right lane blocked
10	5	Downstream	Right lane blocked
11	5	Upstream	Two right lanes blocked
12	5	Downstream	Two right lanes blocked
13	10	Upstream	Right lane blocked
14	10	Downstream	Right lane blocked
15	10	Upstream	Two right lanes blocked
16	10	Downstream	Two right lanes blocked



a) Sensor Set

(b) Detail of Weaving Area

FIGURE 5 WEAVING SECTION NETWORK AND SENSOR SET

TABLE 5 WEAVING SECTION SENSOR SET

Station Spacing	Incident Midway between Two Sensor Stations	Incident Immediately Upstream of a Sensor Station
500 ft. (152 M)	H J L N P R	G I K M O Q S
1000 ft. (305 M)	C E G K O S U W	D F I M Q T V W
2500 ft. (762 M)	B G Q W	A E M U
5000 ft. (1524 M)	E U	A M X

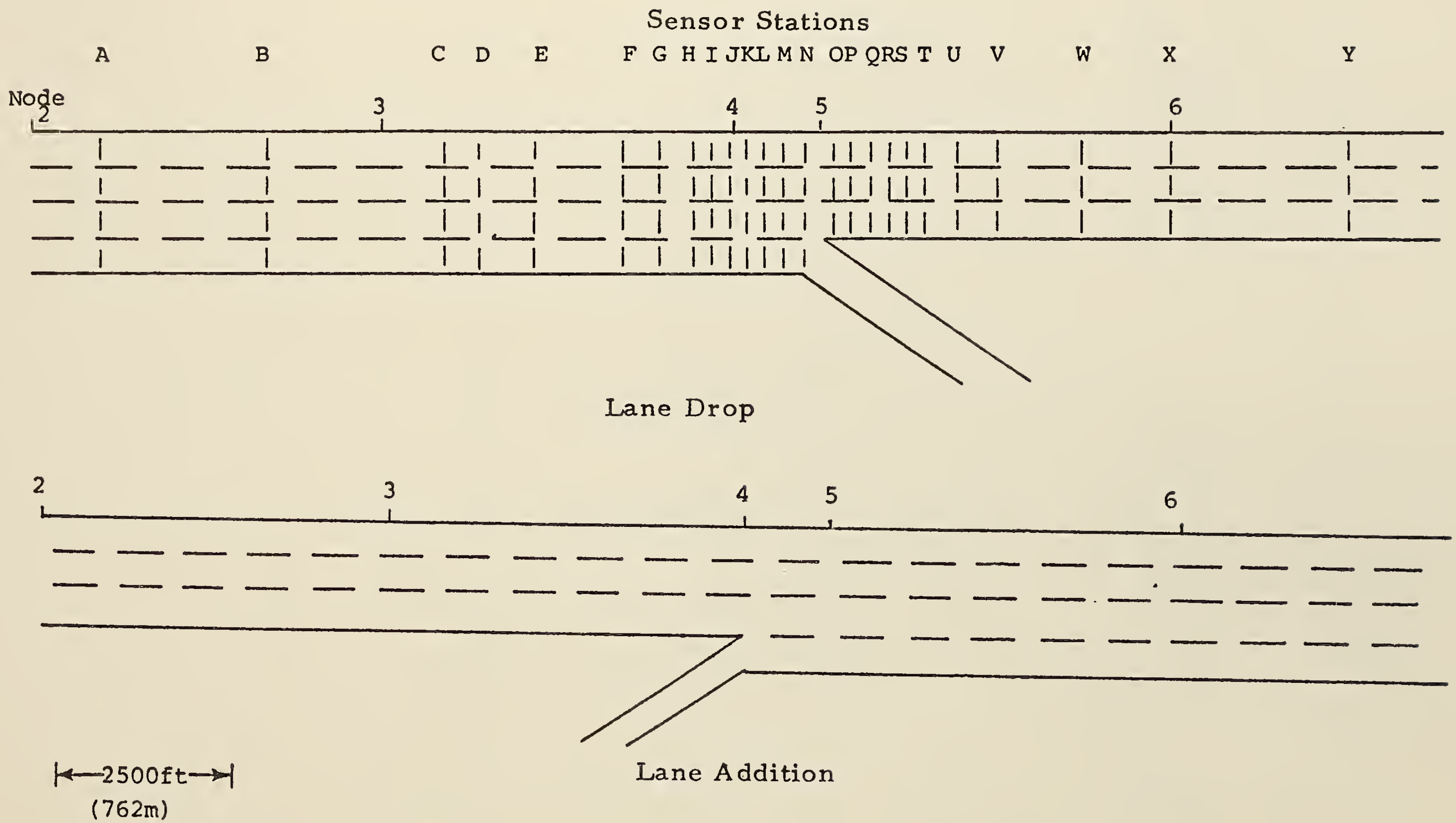


FIGURE 6 NETWORK AND SENSOR STATIONS FOR LANE DROPS AND ADDITIONS

TABLE 6 WEAVING SECTION DATA MATRIX

Run	Weaving Section Length	Ramp Volume	Incident Type
1	1000 ft. (305 M)	700 veh/hr	Right lane
2	1000 ft. (305 M)	700 veh/hr	Left lane
3	1000 ft. (305 M)	700 veh/hr	Center lane
4	1000 ft. (305 M)	700 veh/hr	Two left lanes
5	1000 ft. (305 M)	700 veh/hr	Two right lanes
6-10	1000 ft. (305 M)	1000 veh/hr	Same as 1-5
11-15	2000 ft. (610 M)	850 veh/hr	Same as 1-5
16-20	2000 ft. (610 M)	1150 veh/hr	Same as 1-5
21-25	3000 ft. (915 M)	950 veh/hr	Same as 1-5
26-30	3000 ft. (915 M)	1250 veh/hr	Same as 1-5
31	1000 ft. (305 M)	Variable mainline volumes	No incident
32	2000 ft. (610 M)	Variable mainline volumes	No incident

Alignment Sections

A total of 24 simulation runs were performed to produce the data needed to study the problem of optimum sensor placement on freeway facilities having a change in vertical and horizontal alignment. Three types of alignment changes were studied. These involved the change from a level tangent section to a section with (1) a 3 percent grade, (2) a 6 percent grade, and (3) a 2000 foot (610 M) radius horizontal curve.

TABLE 7 LANE DROPS DATA MATRIX

Run	Configuration	Total Volume (veh/hr)	Incident
1	3 to 4 lanes	3000	Right lane (upstream)
2	3 to 4 lanes	3000	Right lane (downstream)
3	4 to 3 lanes	3000	Right lane (upstream)
4	4 to 3 lanes	3000	Right lane (downstream)
5	4 to 3 lanes	3000	Median lane (taper)
6, 7	Same as 1, 2		Two lane
8-10	Same as 3-5		Two lane
11-20	Same as 1-10	Volume =	4500 veh/hr
21-30	Same as 1-10	Volume =	5400 veh/hr
31	3 to 4 lanes	Variable	No incident
32	4 to 3 lanes	Variable	No incident

The facility simulated was a "pipeline", i.e. a section of freeway containing no ramps. Figure 7 presents the network and universal sensor configuration. The specific sensor stations associated with the candidate spacings may again be found in Table 5.

Two incidents were simulated - a one lane blockage and a two lane blockage. Table 8 displays the data matrix for the alignment section simulation activity.

2.3 OFF-LINE DATA PROCESSING AND ANALYSIS

Further details will now be given regarding the critical factors associated with the processing and analysis of the sensor data. This was done off-line, using the INCES module of the INTRAS model. The factors to be covered are the incident detection algorithms and the measures of algorithm effectiveness.

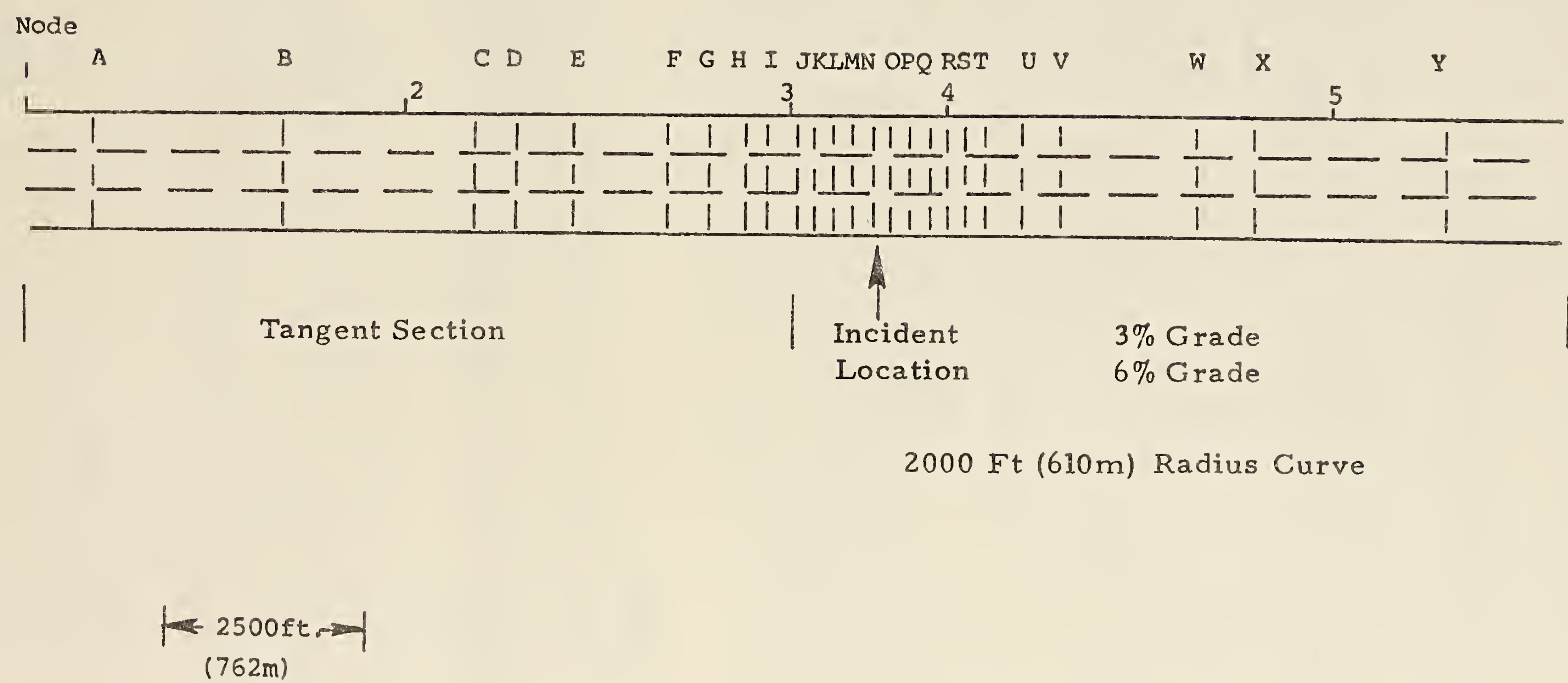


FIGURE 7 ALIGNMENT STUDY NETWORK AND SENSOR SET

TABLE 8 ALIGNMENT DATA MATRIX

Run	Configuration	Total Volume (veh/hr)	Incident
1	0 to 3% grade	3000	Right lane blocked
2	0 to 6% grade	3000	Right lane blocked
3	Tangent to curve	3000	Right lane blocked
4-6	Same as 1-3		Two right lanes blocked
7-12	Same as 1-6	Volume =	3600 veh/hr
13-18	Same as 1-6	Volume =	4200 veh/hr
19-24	Same as 1-6	Volume =	4800 veh/hr
21	0 to 6% grade	Variable	(No incident)

Incident Detection Algorithms

One algorithm employed in this study was the Modified California Algorithm, as described by Sakasita (1). Basically, this algorithm compares three occupancy related parameters to preset thresholds. An incident is detected when each of the test parameters exceeds its threshold. The three occupancy parameters used are:

1) The absolute difference in occupancies (OCCDF) between adjacent sensor stations at a time, J.

2) The percentage difference in occupancies (OCCRDF) between adjacent sensor stations at a time, J.

3) The percentage difference in occupancy over time at the upstream sensor (DOCCTD).

[1] M. Sakasita and A. D. May, Ibid.

The difference between the original algorithm and the modified form implemented here is the time period over which the third parameter, above, is computed. Originally, in the California version, this time period was one minute, whereas the modified value uses five or six minutes.

The second algorithm used was Payne's Algorithm 7 (1). This algorithm is a variant of the California Algorithm, but with a technique of testing the persistence of the incident. Another variation between the two algorithms is Payne's use of the occupancy at the downstream station (DOCC) as an independent parameter. A decision tree for Algorithm 7 is presented in Figure 8.

Measures of Incident Detection Algorithm Effectiveness

As discussed in Section 2.2, some simulations for each geometric feature were conducted without triggering an incident. The purpose was to provide data needed to investigate the matter of false alarms produced by the various candidate sensor configurations. In (2), Payne defines false alarm rate as

$$\alpha = 100 \cdot \frac{N_{FA}}{N_F} \qquad (1)$$

where N_F is the total number of tests performed by the algorithm, and N_{FA} is the total number of false alarm signals generated by the algorithm.

The number of tests performed, N_F, will be computed by multiplying the number of minutes of simulation (algorithms are called once per minute) by the number of sensor stations. The number of false alarm signals, N_{FA}, will be defined as the number of "tentative" incidents located. Should a false alarm persist for a number of minutes, it will still be treated as a single false alarm signal.

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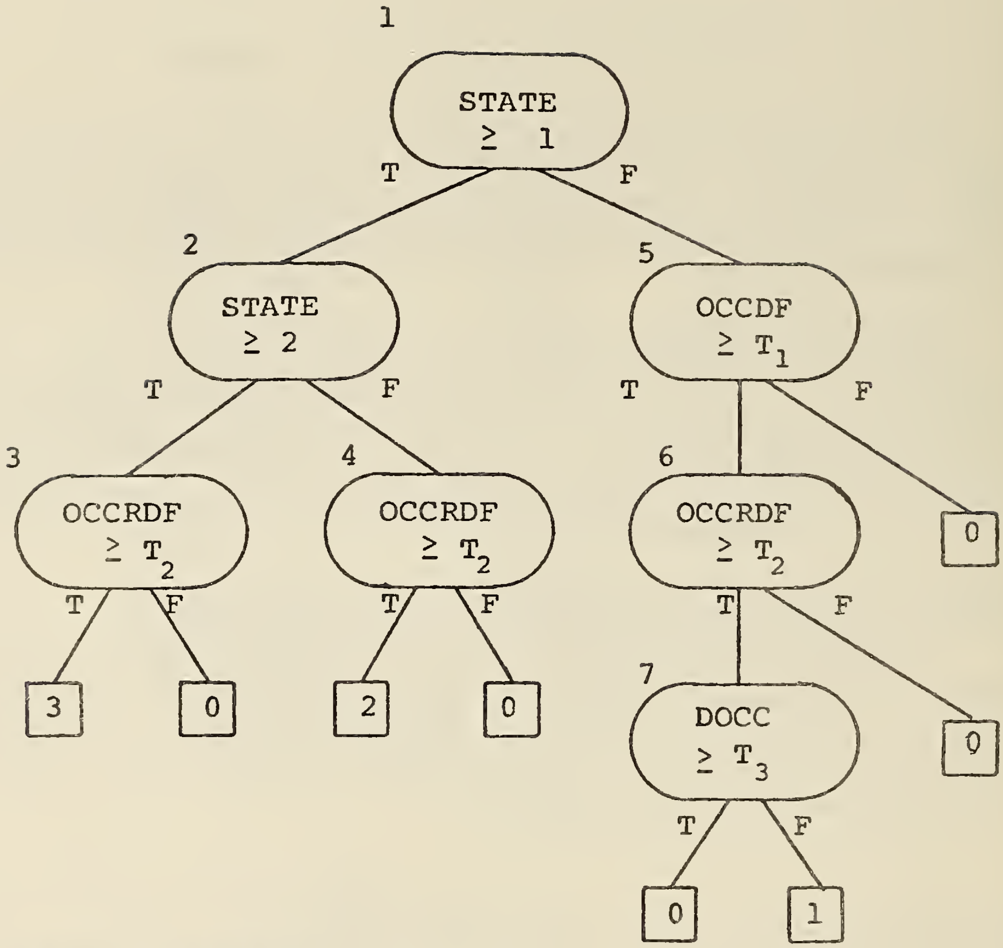
[1] H. J. Payne, E. D. Helfenbein, and H. C. Knobel, Ibid.

[2] Ibid.



State	Designates
0	Incident-free
1	Tentative Incident
2	Incident Occurred
3	Incident Continuing

FIGURE 8 DECISION TREE FOR PAYNE ALGORITHM 7

In the next chapter, the efficacy of a given sensor configuration will primarily be assessed by examining two parameters which measure incident detection algorithm performance: the time, in minutes, to detect an incident (assuming detection occurs) and the incident detection ratio [1]. Time to detect, as noted previously, is computed directly from the INCES analysis. The detection ratio is computed through a comparison of the actual simulated scenario with the incident detection algorithm output. It is defined as:

$$\text{detection ratio} = \frac{\text{number of incidents detected}}{\text{total number of incidents simulated}}$$

---

[1] In designing the experimental program, consideration was given to another measure of effectiveness - the incremental delay, in minutes, incurred by vehicles as a result of an incident. This measure can be derived analytically using procedures described in the work by Owen and Urbanek [2] on Freeway Incident Management (FIM). Details are provided in the Appendix to this report. Included is a discussion of how the technique allowed the extension of the number of specific incident scenarios studied. Although the procedures were implemented as part of the off-line sensor data analysis activity, the delay parameter was not used as a measure of effectiveness to evaluate candidate sensor configurations. An explanation is provided in the Appendix.

[2] J.R. Owen and G.L. Urbanek, "Alternative Surveillance Concepts and Methods for Freeway Incident Management", Volume 2, Report FHWA-RD-77-59, March 1978, PB 279497/AS.

CHAPTER 3

EFFECT OF SENSOR CONFIGURATION ON INCIDENT DETECTION ALGORITHM PERFORMANCE

In this chapter, the results obtained from processing the simulated sensor actuation data through the INCES module will be presented. Using both tabular and graphical formats, the dependence of incident detection algorithm performance upon the particular sensor configuration providing the input data will be quantified. Two effectiveness measures, the detection ratio and the average time to detect (assuming detection occurs), will be employed for this purpose. Consideration will also be given to the matter of false alarms. A separate presentation will be made for each of the four freeway geometric features simulated by the INTRAS model. At the beginning of each section, the matter of validating the flow levels produced by the simulation against results obtained from field measurements will be very briefly addressed.

3.1 MAINLINE FREEWAY SECTION

Consideration will first be given to the deployment of sensors on freeway networks consisting entirely of tangential sections of roadway which have a level grade.

Flow Level Validation

The ability of the INTRAS simulator to replicate conditions in the field can be assessed from the data presented in Table 9.

Note that the actual source of bottleneck flow rate data from the field is Volume 2, Table 5 of an FHWA report on Freeway Incident Management (FIM) by Owen and Urbanek (1). A comparison with the simulation is difficult, however, because this FIM data represents an average over incidents from more than one freeway facility. Fortunately, identical field values for the three lane one-directional case were presented by Goolsby (2) in his study of incidents on the Gulf Freeway in Houston. The fictitious, three lane one-directional network described in Section 2.2 is similar, having ramps which are regularly spaced and fairly close together.

[1] J.R. Owen and G. L. Urbanek, Ibid.

[2] M.E. Goolsby, "Influence of Incidents on Freeway Quality of Service", Highway Research Record 349, 1971.

TABLE 9 BOTTLENECK FLOW RATES FOR VARIOUS INCIDENTS (VEHICLES/MINUTE)

Lanes Blocked		Number of One-Directional Freeway Lanes 3	4
1	Simulation	47	72
	Field	45 (1)	72 (2)
2	Simulation	23	46
	Field	20 (1)	43 (2)

The comparison looks very good. However, it may to some degree be accidental since the fictitious network simulated herein was not intentionally designed to replicate the Gulf Freeway, and a calibration of imbedded values was consequently not performed.

Comparative Performance of Incident Detection Algorithms

In considering the results which follow, the reader should bear in mind that this study was concerned with the general problem of how to deploy freeway sensors, in a cost-effective manner, to improve incident detection capability. Its purpose was not to evaluate or optimize the overall performance of the specific incident detection algorithms used to process the study data.

The use of more than one algorithm minimizes the chances of drawing conclusions about sensor placement which would be algorithm dependent. However, erroneous inferences can still be made if, for example, one algorithm performed in a near optimal fashion throughout the study whereas the other performed poorly. Some discussion

[1] M. E. Goolsby, Ibid.

[2] J. R. Owen and G. L. Urbanek, Ibid.

and analysis is therefore warranted on comparative algorithm performance.

Tables 10 and 11 present comparisons of detection ratios and average times to detect for the two algorithms. These results were obtained by averaging over all incidents, traffic conditions, and incident locations relative to sensor stations simulated on the mainline networks. Note that for both the three and four lane one-directional freeways, Payne's Algorithm No. 7 detects fewer of the incidents (a lower detection ratio) involving single lane blockages. When two lanes are blocked by an incident, however, the Payne Algorithm detects more frequently than the Modified California Algorithm. These results hold consistently over all station spacings for both a full or partial lane instrumentation. If an incident is detected, the Payne Algorithm will detect it faster than the California Algorithm for nearly every sensor configuration studied.

At this point, it should be noted that the threshold values used for both algorithms were those recommended by Payne, Helfenbein, and Knobel (1). These values, which are defined and given in Table 12, were not tailored to the individual networks or traffic flow conditions described in Chapter 2. A small study was performed to assess the sensitivity of algorithm performance to changes in the threshold values. The results presented in Tables 10 and 11 were not affected over the narrow range of values which were considered.

Effect of Station Spacing and Incident Severity

Figures 9-12 present the time to detect as a function of the difference between the arrival demand and the discharge capacity at the incident site for each station spacing under consideration. This difference is a direct indication of incident severity in that it is the rate at which the queue grows upstream of the incident. As this difference increases, the incident becomes more severe.

Referring to Figure 9 for the 500 foot (152 M) spacing, it is apparent that the time to detect increases as the incident severity is reduced. The reason for this is that when the queue grows more slowly, it takes a longer time for its effects to be felt at the upstream sensor station of the pair bracketing the incident.

[1] H. J. Payne, E. D. Helfenbein and H. C. Knobel, Ibid.

TABLE 10 COMPARISON OF MEASURES OF EFFECTIVENESS FOR VARIOUS INCIDENT DETECTION ALGORITHMS (THREE LANE ONE DIRECTIONAL FREEWAY)

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect (Minutes)	Detection Ratio	Time to Detect (Minutes)
One Lane Blocked				
500 feet (152 M)				
Full	13/16	6.9	8/16	3.7
Partial	11/16	7.1	8/16	4.3
1000 feet (305 M)				
Full	13/16	7.5	8/16	6.3
Partial	10/16	8.8	8/16	6.4
2500 feet (762 M)				
Full	11/16	10.0	6/16	6.5
Partial	11/16	10.9	6/16	6.5
5000 feet (1524 M)				
Full	8/16	13.1	6/16	11.0
Partial	9/16	14.3	6/16	11.0
Two Lanes Blocked				
500 feet (152 M)				
Full	16/16	4.1	16/16	2.9
Partial	16/16	3.7	16/16	2.8
1000 feet (305 M)				
Full	15/16	4.6	16/16	3.7
Partial	16/16	4.6	16/16	3.8
2500 feet (762 M)				
Full	13/16	8.2	16/16	7.2
Partial	16/16	7.8	16/16	7.3
5000 feet (1524 M)				
Full	9/16	10.3	11/16	10.4
Partial	10/16	10.8	12/16	10.7

TABLE 11 COMPARISON OF MEASURES OF EFFECTIVENESS FOR VARIOUS INCIDENT DETECTION ALGORITHMS (FOUR LANE ONE-DIRECTIONAL FREEWAY)

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 feet (152 M)				
Full	9/16	8.3	9/16	4.7
Partial	12/16	6.6	11/16	4.3
1000 feet (305 M)				
Full	13/16	8.8	9/16	5.4
Partial	11/16	6.5	11/16	5.7
2500 feet (762 M)				
Full	10/16	10.8	8/16	7.9
Partial	5/16	9.7	7/16	7.1
5000 feet (1524 M)				
Full	5/16	12.8	6/16	11.0
Partial	3/16	12.5	6/16	11.2
Two Lanes Blocked				
500 feet (152 M)				
Full	12/16	5.3	16/16	4.1
Partial	14/16	5.6	16/16	4.1
1000 feet (305 M)				
Full	12/16	5.5	16/16	4.8
Partial	14/16	5.8	16/16	4.5
2500 feet (762 M)				
Full	13/16	7.6	16/16	8.3
Partial	12/16	8.3	14/16	7.5
5000 feet (1524 M)				
Full	8/16	10.3	8/16	9.5
Partial	7/16	11.0	8/16	9.6

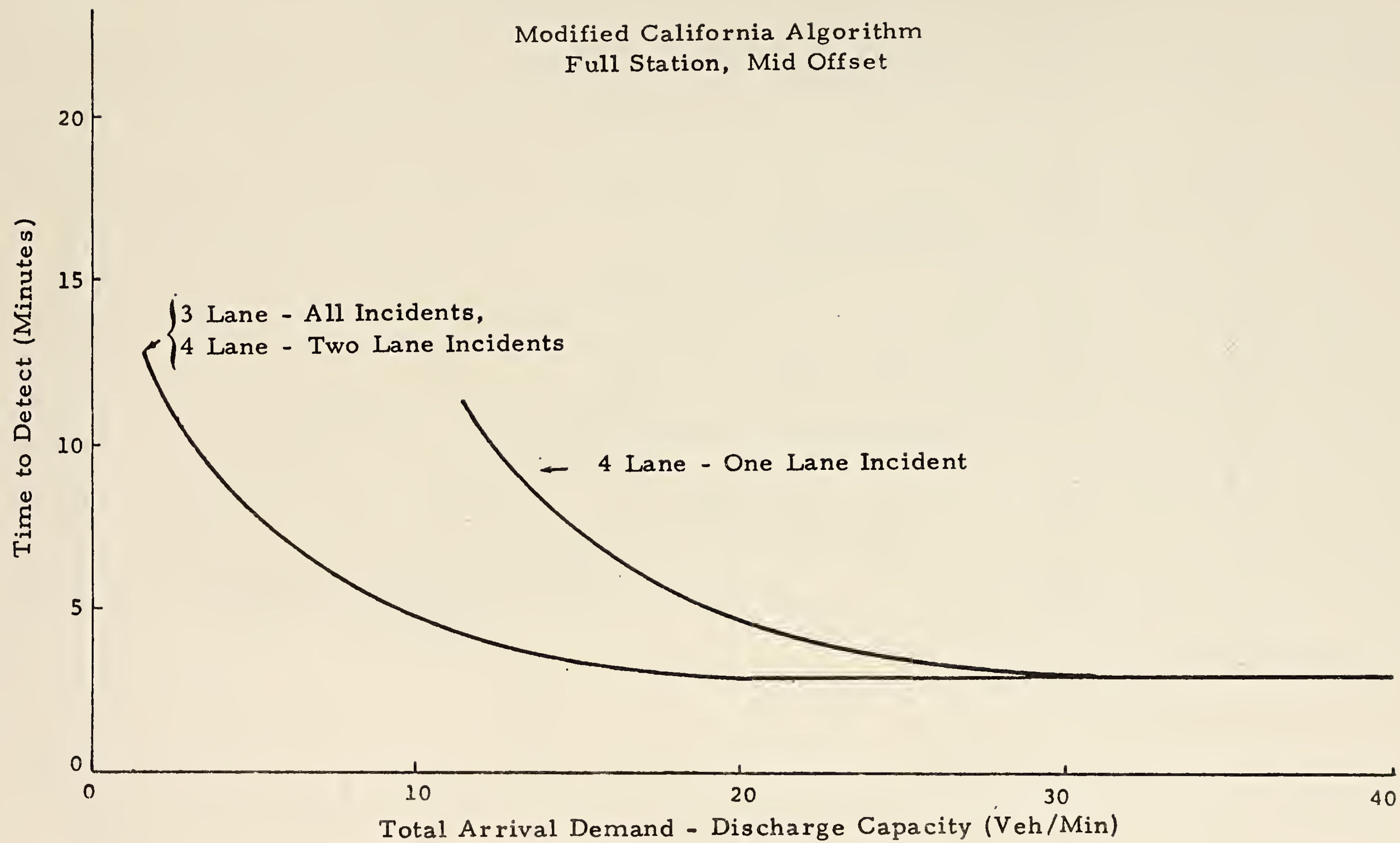


FIGURE 9 MAINLINE TIME TO DETECT 500 FOOT (152 M) SPACING

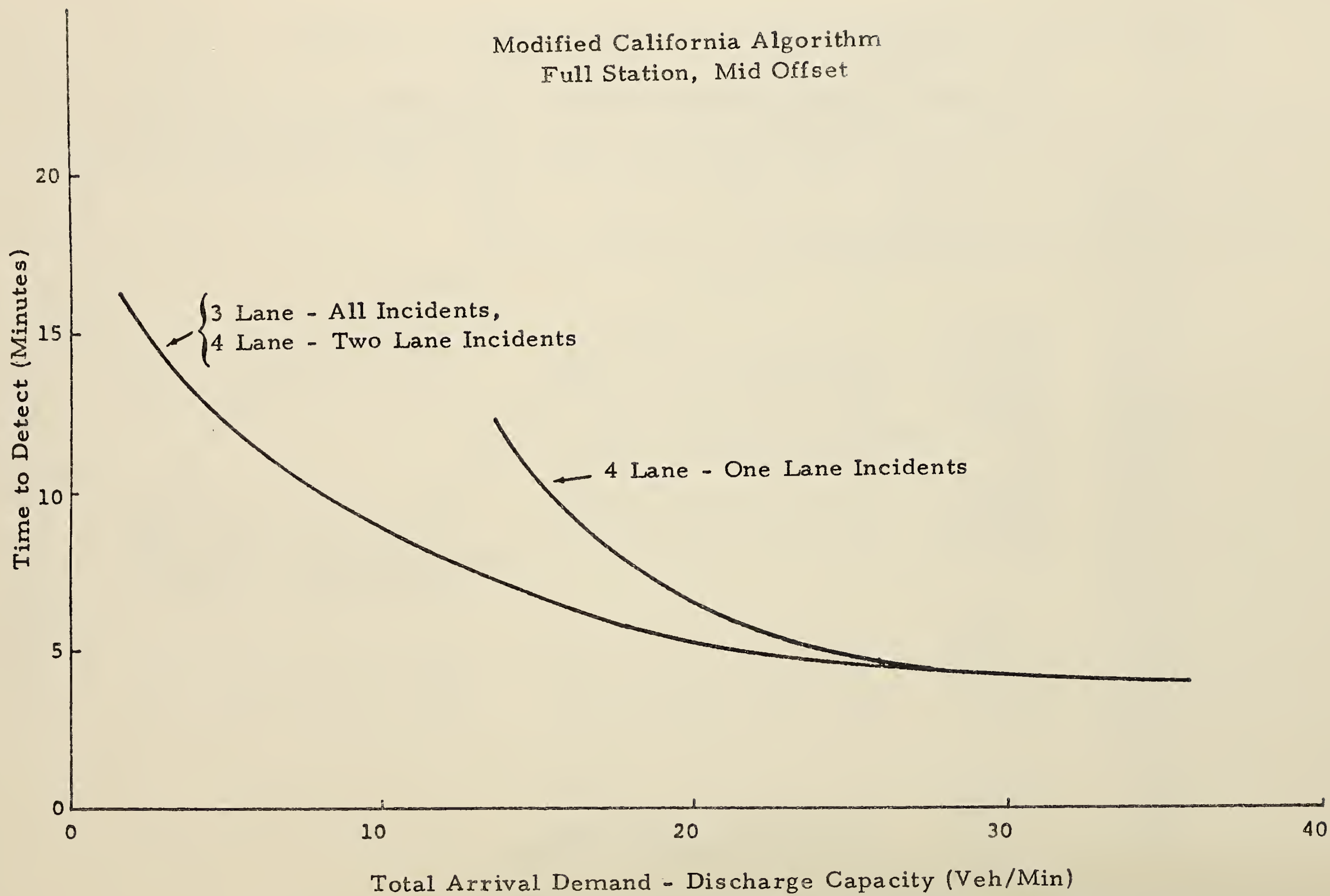


FIGURE 10 MAINLINE TIME TO DETECT 1000 FOOT (305 M) SPACING

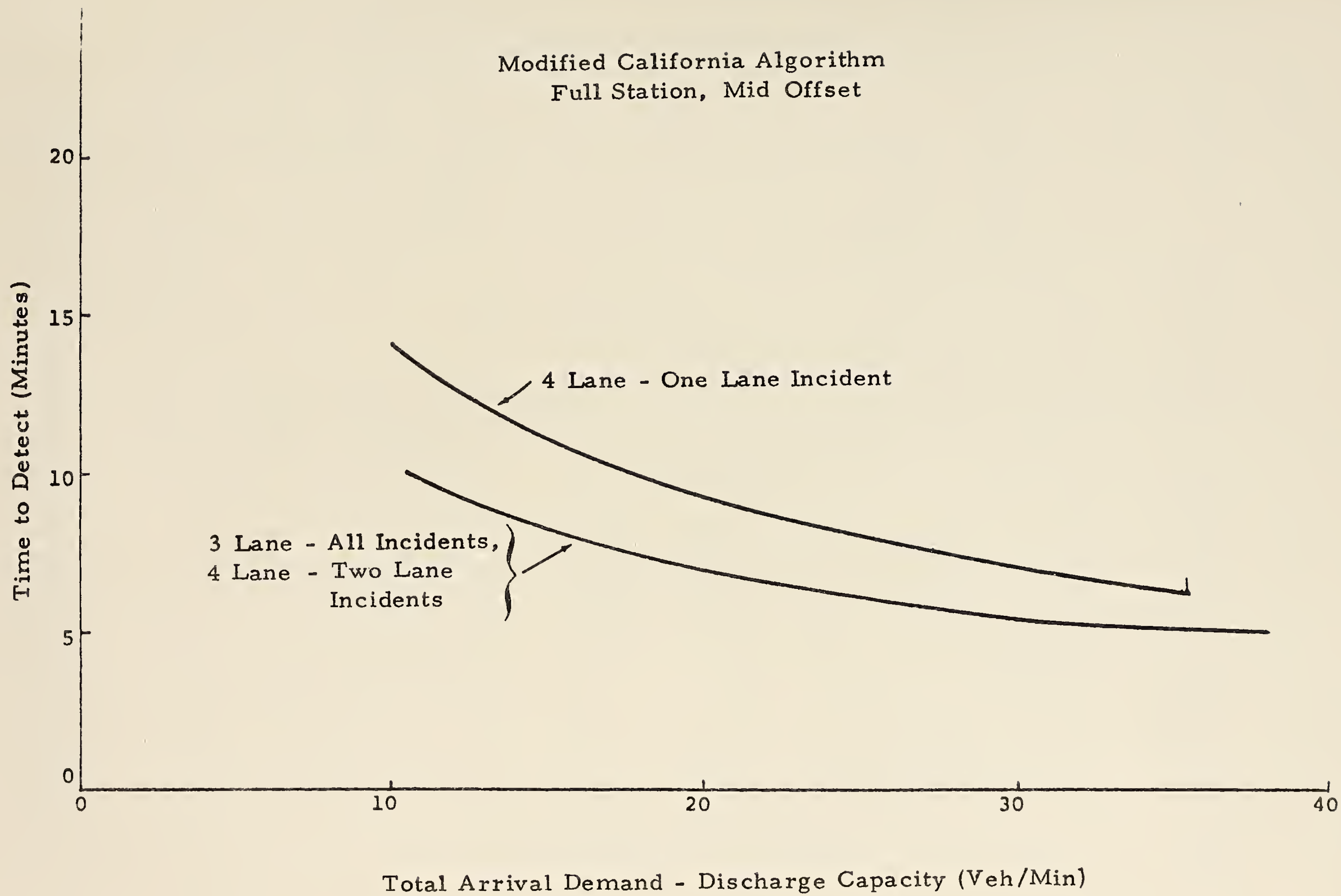


FIGURE 11 MAINLIJE TIME TO DETECT 2500 FOOT (762 M) SPACING

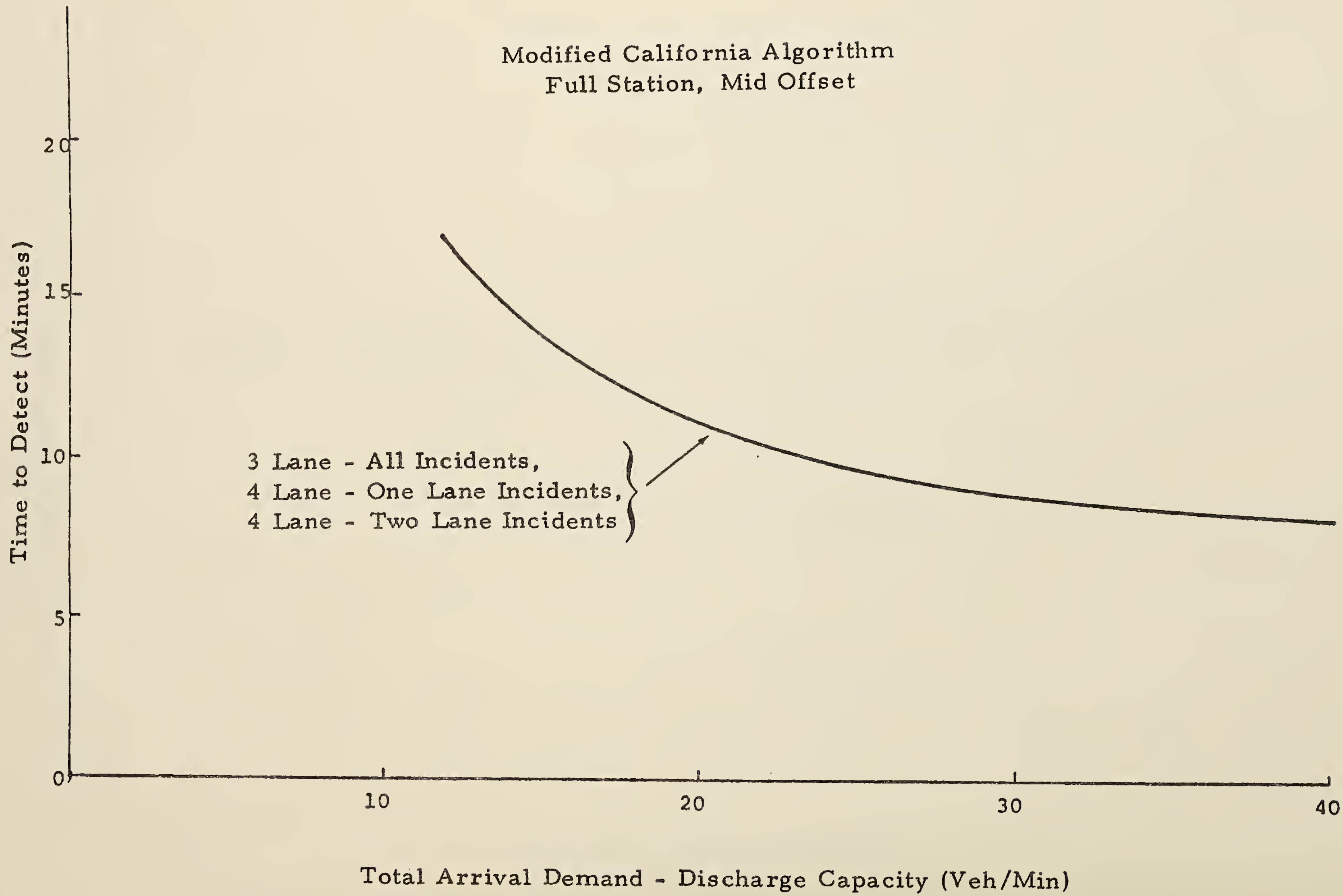


FIGURE 12 MAINLINE TIME TO DETECT 5000 FOOT (1524 M) SPACING

TABLE 12 PARAMETER THRESHOLD VALUES USED WITH INCIDENT DETECTION ALGORITHMS

Parameter Threshold Values

Algorithm	1	2	3
Modified California	Spatial difference in occupancies	Percent spatial difference in occupancies	Relative temporal difference in downstream occupancy
	29.90	0.685	-1.959
Payne No. 7	Spatial difference in occupancies	Percent spatial difference in occupancies	Downstream occupancy
	21.60	0.301	13.90

Both three and four lane one-directional freeway situations are shown in Figure 9. For a four lane one-directional freeway with a two lane blockage it was found that the time to detect is identical to that of a three lane one-directional freeway with one and two lane blockages. Since the one lane blockage on a four lane facility has a clearly less severe effect upon traffic than a corresponding incident has on a three lane roadway, it is not surprising that a longer time is needed to detect that blockage. At freeway volume levels closer to capacity, any incident causes severe effects. Hence both curves asymptote to some low value of time to detect. This value is dependent upon the detection algorithm threshold values and the frequency at which the algorithm is exercised. In this study, both algorithms were updated at one minute intervals.

The effects of station spacing upon time to detect can be seen by comparing this set of figures. In general, as station spacing is increased, the time to detect also increases, Moreover, the clear

pattern of difference between three and four lane facilities becomes blurred. At a spacing of 5000 feet (1524 M), no difference between results for three and four lane one-directional freeways is discernable.

Station spacing seems to have a nearly linear effect upon the minimum time to detect. Table 13 presents this variation.

The effect of station spacing upon the detection ratio can be seen by again referring to Tables 10 and 11. In general, detection ratios do not degrade markedly until spacing increases beyond 2500 feet (762 M).

Effect of Offset and Lane Configuration at a Given Station

The effect of a shift in incident location from midway between consecutive sensor stations to a position close to the downstream station causes an increase in the time to detect. Some representative results are shown in Figure 13. The minimum time to detect seems to be sensitive to station spacing, increasing by about four minutes for the two locations considered. As the incident becomes less severe, the effect of incident location becomes even more critical as station spacing increases.

These results are not unexpected. Since the incident detection algorithms all compare traffic flow variables at pairs of sensor stations, the farther the incident occurs downstream of the upstream station in a pair, the longer it takes for the effects to be felt. Clearly, this effect, coupled with long station spacings, means that many incidents of short duration or of a less severe nature will be missed.

A comparison of the effects of sensor lane configuration at a given station was made. These results, shown in Table 14, show that under certain conditions, the partial configuration led to a more rapid detection of incidents than the full station. This seems to occur when the incident blocks a lane in which sensors are located. However, when the results were subjected to statistical hypothesis testing, no significant differences in performance were observed between the full and partial sensor stations.

False Alarm Study

As indicated in the previous chapter, some simulations with no incidents were run to investigate the false alarm rate for the various candidate configurations. The results are presented in Table 15.

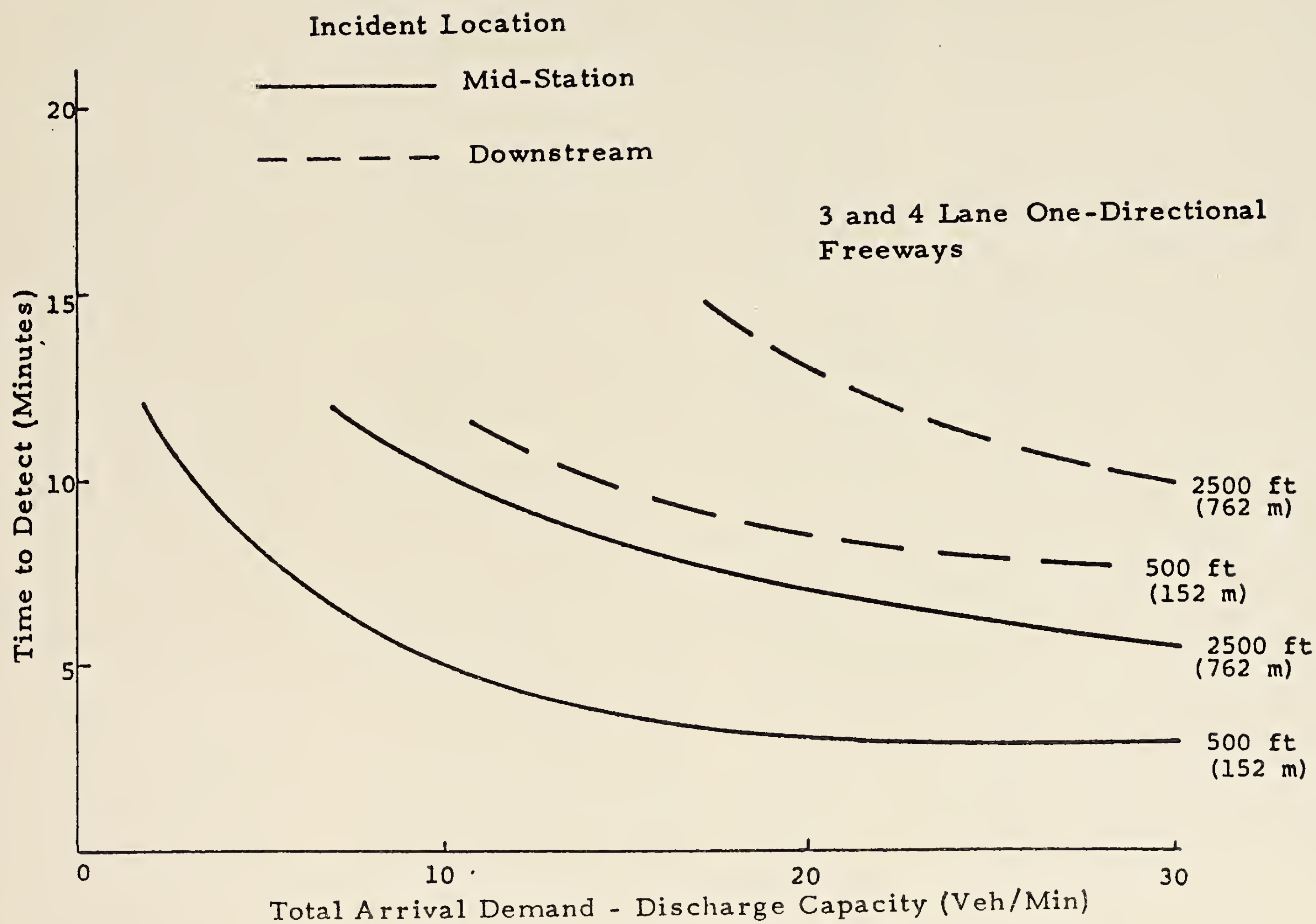


FIGURE 13 EFFECT OF INCIDENT LOCATION UPON TIME TO DETECT FOR THE MODIFIED CALIFORNIA ALGORITHM

TABLE 13 MAINLINE MINIMUM TIME TO DETECT

Sensor Station Spacing	Time to Detect
500 feet (152 M)	3 minutes
1000 feet (305 M)	4 minutes
2500 feet (762 M)	5 minutes
5000 feet (1524 M)	8 minutes

False alarms are only detected at the smallest station spacings. There is no indication that the switch from a full to partial lane instrumentation at a given station has any effect upon false alarm rates.

Ideally, the threshold values for the detection algorithms should have yielded false alarm rates on the order of 0.1 percent. The fact that threshold values were not optimized for the simulated networks would account for the observed false alarm rates being higher than postulated.

On and Off Ramp Study

The purpose of the ramp study is to determine whether the location of sensor stations is affected by the presence of on and off ramps. Table 4 defines the sixteen INTRAS runs which were performed to produce simulated detector actuation data. Analysis of subsets of this data using each of the two incident detection algorithms employed in this study produced the 32 cases for on ramps shown in Table 16 and the 32 cases for off ramps shown in Table 17. These tables present the time to detect for each individual analysis case.

For the on ramp study, comparison of Condition 1 (sensor A upstream of the on ramp) with Condition 2 (sensor station A downstream of the on ramp) reveals no clear trend on which sensor position gives the best performance. Comparison of Condition 3 (sensor B upstream of the on ramp) with Condition 4 (sensor B downstream of the on ramp) likewise is inconclusive. However, for off ramps, Condition 4 always produced a time to detect which was less than or equal to the Condition 3 sensor position. Results were inconclusive when Conditions 1 and 2 were compared

In a further attempt to analyze the information, all of the data points from Conditions 1 and 3 (representing the condition of a sensor station upstream of a ramp) were combined. This yields a total of 16 data points.

TABLE 14 COMPARISON OF FULL AND PARTIAL SENSOR CONFIGURATIONS - MAINLINE GEOMETRY

Algorithm: Modified California
Differences (Full Station-Partial Station)

	One-Directional Three Lane Freeway		One-Directional Four Lane Freeway	
	Difference in Detection Ratio	Time to Detect (Minutes)	Difference in Detection Ratio	Time to Detect (Minutes)
One Lane Blocked				
500 feet (152 M)	2/16*	-0.2*	-3/16	1.7
1000 feet (305 M)	3/16	-1.3	2/16	2.3
2500 feet (762 M)	0	-0.9	5/16	1.1
5000 feet (1524 M)	-1/16	-1.2	2/16	0.3
Two Lanes Blocked				
500 feet (152 M)	0	0.4	-2/16	-0.3
1000 feet (305 M)	-1/16	0	-2/16	-0.3
2500 feet (762 M)	-3/16	0.4	1/16	-0.7
5000 feet (1524 M)	-1/16	-0.5	1/16	-0.7

*A positive quantity indicates that the value of the measure for a full configuration is larger than the corresponding value for the partial configuration, while a negative quantity indicates a larger value for the partial configuration.

TABLE 15 PERCENT FALSE ALARMS-MAINLINE SIMULATION

	Modified California		Payne's No. 7	
	3-lane	4-lane	3-lane	4-lane
500 ft. (152 M)				
Full	1.1	1.7	0.4	0.4
Partial	2.0	1.3	0.4	0.4
1000 ft. (305 M)				
Full	0	0	0	0
Partial	0	0	0	0
2500 ft. (762 M)				
Full	0	0	0	0
Partial	0	0	0	0
5000 ft. (1524 M)				
Full	0	0	0	0
Partial	0	0	0	0

A similar aggregation was performed for conditions 2 and 4 (representing the case of a sensor station downstream of a ramp). These two aggregates were compared on a point by point basis to see how many times sensor stations upstream of a ramp detected the incident faster than sensor stations placed downstream of a ramp.

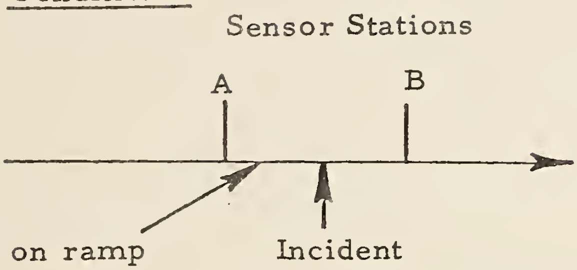
The results of this analysis are summarized in Table 18. In the case of on ramps, sensor stations upstream of the ramp detected the incident faster 4 times while stations downstream of the ramp detected incidents faster 4 times. Thus, sensor station position relative to an on ramp does not seem to influence time to detect.

The reasons for these results are clear. For off ramps, a percentage of the traffic flowing past the incident leaves the facility at the ramp. Therefore, over a given period of time, occupancy at the sensors downstream of the ramp is lower than occupancies computed upstream of the ramp. Moreover, the greater the percentage of vehicles leaving the facility at the ramp, the greater this difference becomes. It is the lower occupancy levels at the sensor station downstream of the

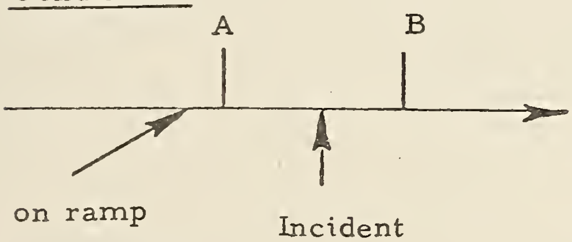
TABLE 16 ON RAMP STUDY - TIME TO DETECT (MINUTES)

	ON RAMP VOLUME (VEH/HR)	
	500	1000
Condition 1		
One-lane blocked	3(3)*	2(2)
Two-lanes blocked	3(3)*	5(2)
Condition 2		
One-lane blocked	5(4)	2(2)
Two-lanes blocked	3(3)	2(2)
Condition 3		
One-lane blocked	4(3)	6(6)
Two-lanes blocked	4(3)	6(4)
Condition 4		
One-lane blocked	4(4)	7(5)
Two-lanes blocked	3(3)	4(4)

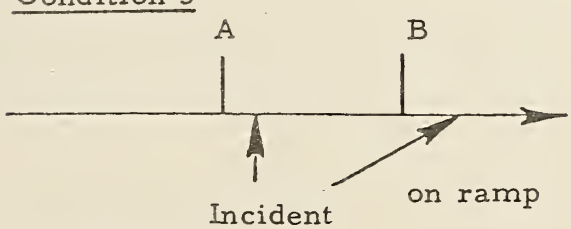
Condition 1



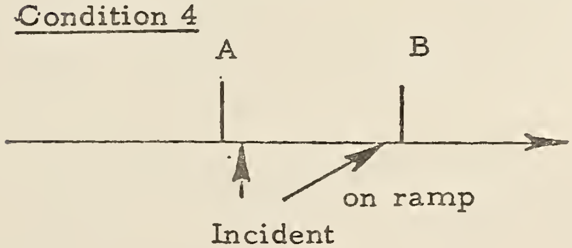
Condition 2



Condition 3



Condition 4



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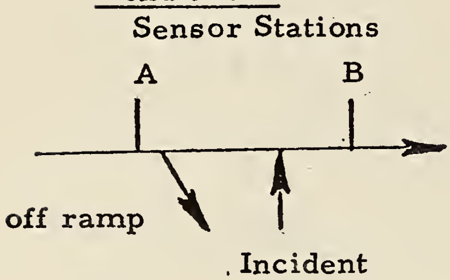
* 3 - Value for Modified California Algorithm

(3) - Value for Payne No. 7 Algorithm

TABLE 17 OFF RAMP STUDY - TIME TO DETECT (MINUTES)

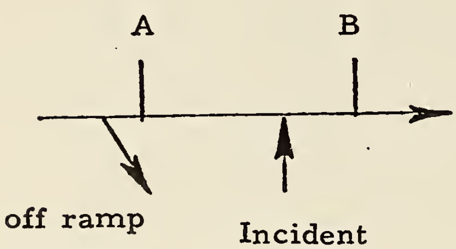
PERCENT VEHICLES EXITING FREEWAY

Condition 1



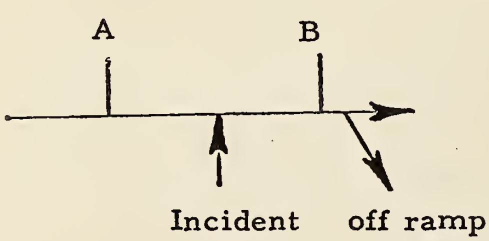
	5%	10%
One-lane blocked	6(5)*	3(2)
Two-lanes blocked	4(3)	2(2)

Condition 2



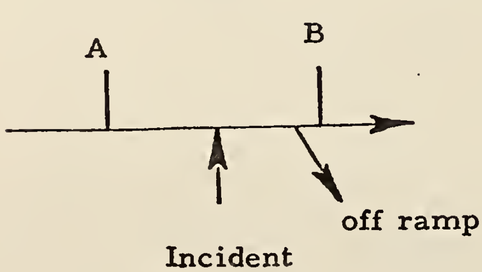
	5%	10%
One-lane blocked	6(6)	2(2)
Two-lanes blocked	5(4)	2(2)

Condition 3



	5%	10%
One-lane blocked	5(4)	7(5)
Two-lanes blocked	4(3)	6(5)

Condition 4



	5%	10%
One-lane blocked	4(4)	6(5)
Two-lanes blocked	3(3)	4(4)

---

* 6 - Value for Modified California Algorithm
(5) - Value for Payne No. 7 Algorithm

TABLE 18 SUMMARY OF RAMP STUDY RESULTS BASED ON A TOTAL OF 16 RUNS

	On-Ramps		Off-Ramps	
	Station Upstream of Ramp	Station Downstream of Ramp	Station Upstream of Ramp	Station Downstream of Ramp
Detects Faster	4	4	2	7
Equal Detection Time	8		7	

ramp which trigger the earlier detection of the incident. Although no effects are observed when sensor stations are varied with respect to on ramps, a preferred sensor location can be deduced using arguments similar to those used to explain the off ramp results.

Referring to Figure 14, the occupancy at sensor station C is higher than at station B due to the traffic entering the road at the on ramp. Consequently, the difference in occupany between A and C is less than that between A and B, thereby leading to a longer time to detect for stations AC than AB.

In summary, there is evidence to support the practice of locating sensor stations upstream of on ramps and downstream of off ramps.

<u>Mainline Section Conclusions</u>

The results of the mainline runs point to station spacings below 2500 feet (762 M). As the spacing is increased from this value, the detection ratio and the time to detect begin to degrade. There are strong indications that the 500 foot (152 M) spacing yields a high degree of false alarms. Therefore, the optimum choice of station spacing lies between 1000 feet (305 M) and 2500 feet (762 M).

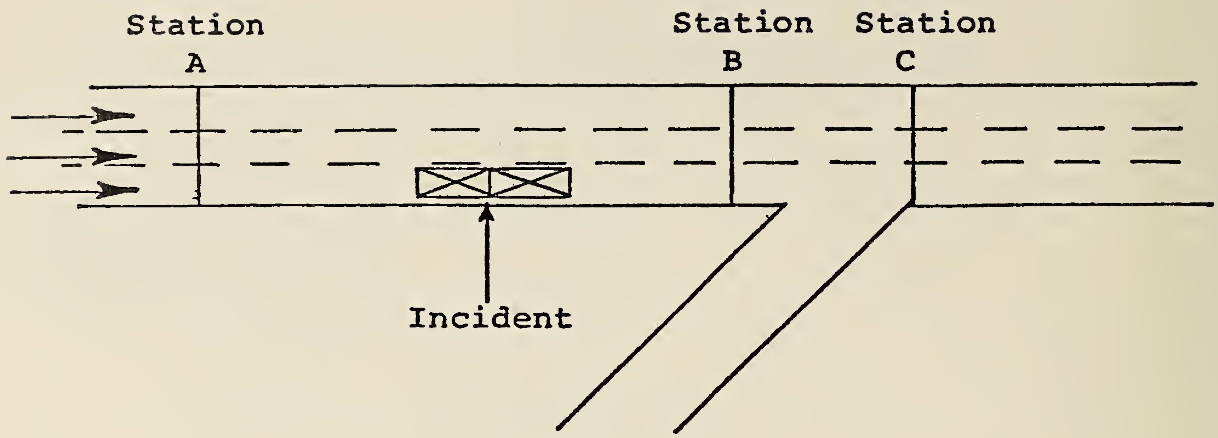


FIGURE 14 ON-RAMP STUDY CONFIGURATION

On the basis of incident detection algorithm performance alone, it is not possible to reach a definitive conclusion regarding whether a full or partial lane instrumentation at a given station is preferable.

There is evidence to indicate that it is advantageous to locate sensor stations immediately upstream of on ramps and immediately downstream of off ramps. This conclusion is tentative and should be studied more closely.

3.2 WEAVING SECTIONS

A summary of the results obtained from the set of simulations involving freeway networks with a weaving area may be found in Tables 19-21. Data presented here was obtained from 32 simulation cases and over 300 analysis runs.

The performance of the simulation model was assessed, as before, by checking the bottleneck flow rates at the incident site. Rates of 71 vehicles per minute and 50 vehicles per minute were found for the one and two lane blockages, respectively. These values are consistent

TABLE 19 WEAVING SECTION DETECTION RATIO AND TIME TO DETECT

Weaving Section Length = 1000 feet (305 M)

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 feet (152 M)				
Full	6/6	3.7	6/6	3.3
Partial	6/6	5.5	6/6	4.0
1000 feet (305 M)				
Full	6/6	5.1	6/6	4.5
Partial	6/6	5.7	6/6	4.5
2500 feet (762 M)				
Full	6/6	7.5	6/6	6.7
Partial	6/6	7.8	6/6	7.0
5000 feet (1524 M)				
Full	0/6	---	4/6	13.0
Partial	0/6	---	4/6	13.0
Two Lanes Blocked				
500 feet (152 M)				
Full	4/4	4.0	4/4	2.8
Partial	3/4	4.3	4/4	2.5
1000 feet (305 M)				
Full	4/4	3.5	4/4	3.0
Partial	4/4	3.5	4/4	3.3
2500 feet (762 M)				
Full	3/4	7.0	4/4	5.8
Partial	4/4	6.3	4/4	5.8
5000 feet (1524 M)				
Full	3/4	10.7	4/4	10.0
Partial	2/4	11.0	4/4	10.3

TABLE 20 WEAVING SECTION DETECTION RATIO AND TIME TO DETECT

Weaving Section Length = 2000 feet (610 M)

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 feet (152 M)				
Full	6/6	5.8	6/6	3.2
Partial	6/6	5.7	5/6	4.2
1000 feet (305 M)				
Full	6/6	5.2	6/6	3.8
Partial	6/6	5.0	6/6	3.8
2500 feet (762 M)				
Full	6/6	7.3	6/6	6.7
Partial	6/6	7.7	6/6	6.7
5000 feet (1524 M)				
Full	1/6	12.0	6/6	13.0
Partial	1/6	11.0	6/6	12.8
Two Lanes Blocked				
500 feet (152 M)				
Full	4/4	3.8	4/4	3.3
Partial	3/4	3.7	4/4	3.5
1000 feet (305 M)				
Full	4/4	4.0	4/4	2.8
Partial	4/4	4.5	4/4	2.8
2500 feet (762 M)				
Full	4/4	5.8	4/4	5.3
Partial	3/4	5.3	4/4	5.5
5000 feet (1524 M)				
Full	3/4	11.0	4/4	9.5
Partial	3/4	11.0	4/4	9.5

TABLE 21 WEAVING SECTION DETECTION RATIO AND TIME TO DETECT

Weaving Section Length = 3000 feet (914 M)

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 feet (152 M)				
Full	4/6	4.0	5/6	4.4
Partial	5/6	4.4	5/6	4.0
1000 feet (305 M)				
Full	5/6	4.8	6/6	4.2
Partial	6/6	5.0	6/6	4.2
2500 feet (762 M)				
Full	6/6	8.5	6/6	6.2
Partial	6/6	8.8	6/6	5.5
5000 feet (1524 M)				
Full	2/6	12.0	6/6	12.0
Partial	3/6	14.7	6/6	12.2
Two Lanes Blocked				
500 feet (152 M)				
Full	4/4	5.3	4/4	2.8
Partial	4/4	4.5	4/4	2.5
1000 feet (305 M)				
Full	3/4	4.0	4/4	3.8
Partial	3/4	3.7	4/4	3.5
2500 feet (762 M)				
Full	4/4	5.8	4/4	4.5
Partial	4/4	5.5	4/4	4.8
5000 feet (1524 M)				
Full	4/4	11.5	4/4	8.8
Partial	2/4	10.5	4/4	8.8

with the four lane mainline results cited earlier in Table 9 (recall that the facilities with a weaving area all contained four lanes).

A comparison of algorithm performance shows that the detection ratios have very little sensitivity to the weaving section length. Payne's No. 7 algorithm consistently detects incidents faster.

Effect of Station Spacing

The data in Tables 19-21 indicate that detection ratios at or near unity were achieved for each of the three station spacings at or below 2500 feet (762 M). A marked reduction in the number of incidents detected is observed however when the 5000 feet (1524 M) station spacing was employed. This is particularly apparent for the Modified California algorithm. The relationship between the time to detect and station spacing is depicted in Figure 15. Results are only displayed for a weaving section length of 1000 feet (305 M). However, very similar curves result if the section length is increased to the 2000 feet (610 M) and 3000 feet (914 M) geometries.

Effect of Lane Configuration at a Given Station

There are no observed differences in either the detection ratio or the time to detect as a result of changes in the sensor configuration at a given station. This conclusion was tested statistically using the Sign test (1) for pairs. The differences between the full and partial configurations were shown not to be significant at the one percent level for all tests.

False Alarm Study

The results of the false alarm study are shown in Table 22. The higher false alarm rate for the Modified California algorithm is due to a lack of stability, i.e. there was oscillation between the "incident" and "incident cleared" signals. Payne's algorithm is more stable in that once a false alarm is detected, no "incident cleared" signal is generated.

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[1] E. L. Crow, F. A. Davis and M. W. Maxfield, Statistics Manual, Dover Publications, 1960.

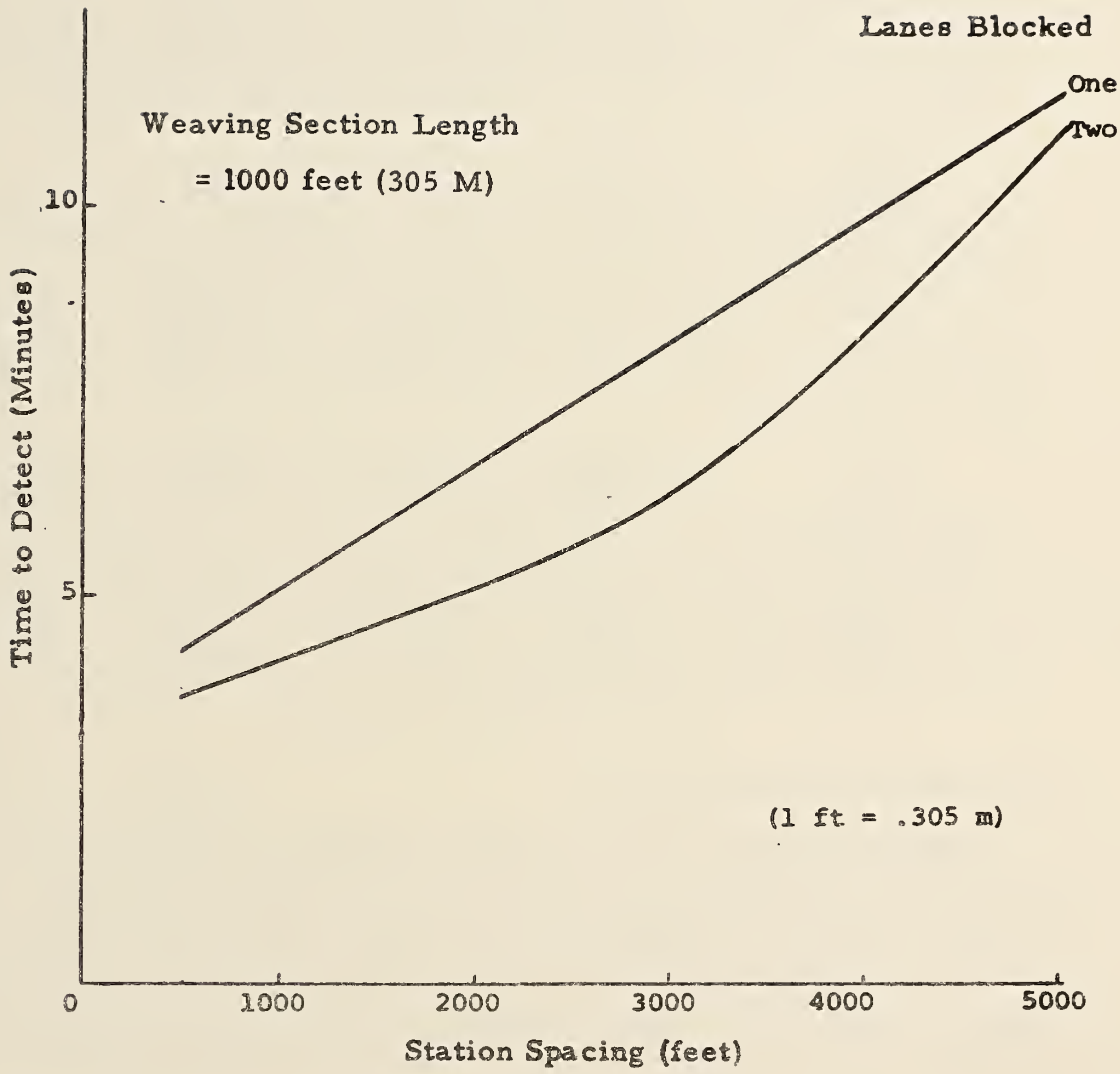


FIGURE 15 WEAVING SECTION -- EFFECT OF STATION SPACING

TABLE 22 WEAVING SECTION FALSE ALARM RATES

	1000 ft. (305 M) Modified California Algorithm	1000 ft. (305 M) Payne's No. 7 Algorithm	2000 ft. (610 M) Modified California Algorithm	2000 ft. (610 M) Payne's No. 7 Algorithm
500 ft. (152 M)				
Full	0.7%	0.2%	0	0
Partial	0	0	0	0
1000 ft. (305 M)				
Full	1.3%	0.3%	0.3%	0.3%
Partial	1.3%	0.3%	1.3%	0.3%
2500 ft. (762 M)				
Full	3.3%	0.7%	3.3%	0.7%
Partial	3.3%	0.7%	4.0%	0.7%
5000 ft. (1524 M)				
Full	4.4%	1.1%	6.7%	1.1%
Partial	5.6%	1.1%	6.7%	1.1%

Weaving Section Conclusions

In general, the smaller the station spacing, the greater the number of incidents detected and the quicker each incident is detected. Large degradation in performance does not occur until station spacing exceeds 2500 feet (762 M). In addition, false alarm rates remain low until a spacing of 2500 feet (762 M) is used. Combining these factors leads to the conclusion that, based upon the geometry of the weaving section and the conditions simulated, station spacings between 1000 feet (305 M) and 2500 feet (762 M) are indicated.

It is not possible to make a choice between the full and partial lane configurations at a given station based upon geometry and flow conditions alone. Since there is no clear advantage to the use of either of the tested configurations, a choice between them must be made on the basis of cost effectiveness analysis.

3.3 LANE DROPS AND ADDITIONS

The results for the freeway networks which contain changes from four to three one-directional lanes and vice-versa can be seen in Tables 23 and 24. This lane drops and additions study encompassed 32 simulation runs and over 300 analysis runs. Because of the changes in geometry occurring on the section of freeway studied, incidents were placed both upstream and downstream of the position of geometry change.

Based upon the results shown in these tables, it appears that an incident is easier to detect, and can be detected faster if it occurs on the narrow portion (three lane section) of the road. This seems to be the case for both the lane drop and the lane addition cases. Conversely, as can be seen in Table 23 for the single lane blockage, the detection ratio is low when the incident occurs in the four lane section.

Effect of Station Spacing and Lane Configuration

There seems to be no major degradation in performance with respect to both time to detect and the detection ratio until station spacing exceeds 2500 feet (762 M). This result is found for both algorithms. No definitive trend was observed in either the detection ratio or the time to detect which could be attributed to the specific sensor configuration deployed at a given station.

False Alarm Study

In the case of lane drops, the false alarm runs showed about a one percent false alarm rate being generated at the 2500 foot (762 M) spacing. No other false alarms were generated at any other spacing. In the case of lane additions, the false alarm runs showed about a three percent false alarm rate at the 500 foot (152 M) spacing. Because of the higher false alarm rate, the 500 foot (152 M) spacing is not recommended.

Lane Drop and Addition Conclusions

The general trends lead to a recommended station spacing of less than 2500 feet (762 M). When false alarm rates are taken into consideration, however, a spacing of greater than 500 feet (152 M) is preferred. Again, choice of full versus partial lane configuration must be left to cost effectiveness considerations.

TABLE 23 LANE CHANGE GEOMETRY – EFFECT OF INCIDENT LOCATION (ONE LANE BLOCKED) (MODIFIED CALIFORNIA)

	Incident Located Upstream of Geometry Change		Incident Located Downstream of Geometry Change	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
Lane Drops				
500 ft (152 M)				
Full	2/3	8.5	2/3	3.0
Partial	3/3	4.7	2/3	4.0
1000 ft (305 M)				
Full	0	-	2/3	10.5
Partial	3/3	4.7	2/3	6.0
2500 ft (762 M)				
Full	2/3	9.9	2/3	6.5
Partial	0	-	2/3	6.5
5000 ft (1524 M)				
Full	0	-	1/3	11.0
Partial	1/3	14.0	1/3	11.0
Lane Addition				
500 ft (152 M)				
Full	2/3	10.5	0	-
Partial	3/3	5.3	0	-
1000 ft (305 M)				
Full	3/3	6.0	0	-
Partial	3/3	5.0	1/2	9.0
2500 ft (762 M)				
Full	2/3	5.0	0	-
Partial	2/3	5.0	0	-
5000 ft (1524 M)				
Full	2/3	8.0	0	-
Partial	2/3	8.5	0	-

TABLE 24 LANE CHANGE GEOMETRY — EFFECT OF INCIDENT LOCATION (TWO LANES BLOCKED) (MODIFIED CALIFORNIA)

	Incident Located Upstream of Geometry Change		Incident Located Downstream of Geometry Change	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
Lane Drops				
500 ft (152 M)				
Full	3/3	4.3	3/3	3.0
Partial	3/3	4.3	3/3	3.0
1000 ft (305 M)				
Full	3/3	4.0	3/3	4.3
Partial	3/3	3.3	3/3	4.0
2500 ft (762 M)				
Full	2/3	8.0	3/3	6.7
Partial	0	-	3/3	6.3
5000 ft (1524 M)				
Full	1/3	10.0	1/3	9.0
Partial	1/3	9.0	1/3	12.0
Lane Addition				
500 ft (152 M)				
Full	3/3	2.3	3/3	3.3
Partial	3/3	2.3	3/3	4.0
1000 ft (305 M)				
Full	3/3	3.0	3/3	5.0
Partial	3/3	3.0	3/3	5.3
2500 ft (762 M)				
Full	3/3	5.0	3/3	6.7
Partial	3/3	6.0	2/3	5.0
5000 ft (1524 M)				
Full	2/3	6.5	2/3	8.0
Partial	2/3	6.5	2/3	8.0

3.4 CHANGES IN VERTICAL AND HORIZONTAL ALIGNMENT

The effects of changes in vertical and horizontal alignments upon sensor placement depend entirely on the response of traffic flow to the changes involved. Therefore, it is useful to assess the effect of changes in alignment upon incident related measures. A total of 25 simulation runs and over 250 analysis runs were used in this study. Table 25 presents a comparison of the discharge capacity (bottleneck flow rate) downstream of the incident. The zero percent grade data was obtained from the mainline on ramp and off ramp study. Overall changes in vertical alignment have a much greater effect on bottleneck flow rates than do changes in horizontal alignment. With proper use of superelevation, there should be no effect. The effect of a three percent grade is to reduce the flow rates by about six vehicles per minute. This is consistent for both one and two lane blockages. Increasing the grade to six percent reduces the flow rate by only an additional one or two vehicles per minute.

In Tables 26-28, incident detection algorithm performance results are presented for each type of alignment change simulated by the INTRAS model. Note that the comparisons between the detection algorithms discussed previously are still valid. When detection occurs, Payne's No. 7 algorithm detects faster.

Effect of Station Spacing and Grade

Figure 16 presents the effects of grade on time to detect for two station spacings as a function of incident severity. The effects of grade are minimized as the severity of the incident is increased. As incident severity becomes less, increasing the grade lengthens the time to detect. This effect is non-linear, becoming more pronounced at longer station spacings.

The explanation for the observed effects lies in the fact that the grade itself can be considered a perpetual, low severity incident. This causes higher densities (for a given flow level) and, consequently, higher occupancy levels at sensor stations on the grade. One of the considerations used by the incident detection algorithm was a reduction of occupancy at the downstream sensor. Therefore, incident signals are delayed because the rate of occupancy reduction at the downstream station is slower when that station is on a grade.

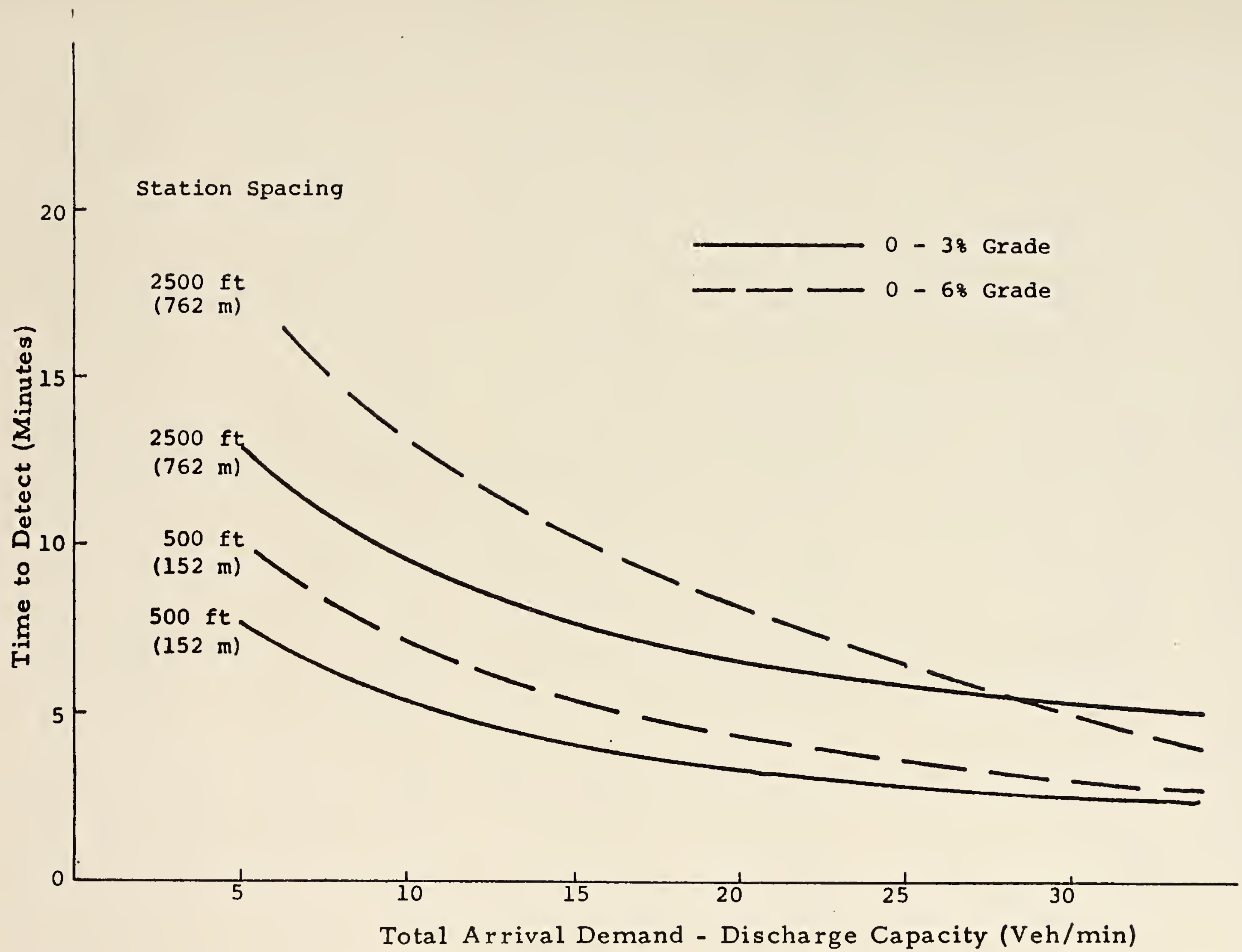


FIGURE 16 EFFECT OF GRADE ON TIME TO DETECT

TABLE 25 EFFECT OF ALIGNMENT ON BOTTLENECK FLOW RATES IN VEHICLES PER MINUTE FOR A THREE-LANE FACILITY

	Alignment			
	Vertical			Horizontal
	0%	0-3%	0-6%	2000 ft. (610 M)
One Lane Blocked	52	46	44	49
Two Lanes Blocked	29	23	23	24

Although the presence of grade does, in general, delay the detection of the incident, it does not affect the pattern of results with regard to station spacing. As the data in Tables 26-28 suggests, large increases in the time to detect or reductions in the detection ratio do not occur until station spacing is lengthened beyond 2500 feet (762 M).

The curves presented in Figure 16 were compared with those presented for the three lane mainline facility in Figures 9 and 11. The comparison showed that they were nearly identical to the curves for the 0-3% grade shown in Figure 16. This indicates that the turbulence caused by the ramps on the mainline facility was roughly equal in effect to that caused by the change in alignment.

Effect of Lane Configuration at a Given Station

As before, statistical tests were run to compare the effects of sensor configuration at a given station. Six "Sign Tests" were run for the two effectiveness measures over the three alignment configurations. In no case did a significant difference exist between the full and partial configurations.

False Alarm Study

A false alarm study was conducted on the 0-6 percent alignment change. No false alarms were generated during the run for any station spacing or sensor configuration at a given station. False alarms seem to be generated as a result of turbulence caused by ramps or weaving sections.

TABLE 26 RESULTS OF THE ALIGNMENT STUDY — GEOMETRY: TANGENT TO HORIZONTAL CURVE

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 ft (152 M)				
Full	·3/4	4.7	4/4	3.5
Partial	4/4	7.2	4/4	6.0
1000 ft (305 M)				
Full	3/4	5.7	3/4	4.0
Partial	3/4	6.3	3/4	4.0
2500 ft (762 M)				
Full	2/4	6.0	3/4	7.0
Partial	3/4	7.0	3/4	7.0
5000 ft (1524 M)				
Full	2/4	10.0	2/4	9.0
Partial	2/4	10.5	2/4	9.0
Two Lanes Blocked				
500 ft (152 M)				
Full	4/4	3.8	4/4	2.8
Partial	4/4	2.8	4/4	2.3
1000 ft (305 M)				
Full	4/4	3.3	4/4	3.0
Partial	4/4	3.3	4/4	3.0
2500 ft (762 M)				
Full	4/4	5.8	4/4	5.0
Partial	4/4	5.8	4/4	5.8
5000 ft (1524 M)				
Full	4/4	9.5	4/4	8.5
Partial	4/4	9.5	4/4	8.5

TABLE 27 RESULTS OF THE ALIGNMENT STUDY — GEOMETRY: LEVEL TO 3% GRADE

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 ft (152 M)				
Full	4/4	4.3	4/4	3.3
Partial	4/4	6.0	4/4	3.3
1000 ft (305 M)				
Full	4/4	5.3	4/4	4.0
Partial	4/4	4.5	4/4	4.0
2500 ft (762 M)				
Full	3/4	6.7	3/4	6.0
Partial	3/4	6.0	3/4	5.7
5000 ft (1524 M)				
Full	2/4	9.0	2/4	8.0
Partial	2/4	8.5	2/4	8.5
Two Lanes Blocked				
500 ft (152 M)				
Full	4/4	2.5	4/4	2.3
Partial	4/4	2.3	4/4	2.3
1000 ft (305 M)				
Full	4/4	3.3	4/4	3.3
Partial	4/4	3.3	4/4	3.3
2500 ft (762 M)				
Full	4/4	5.0	4/4	4.8
Partial	4/4	4.8	4/4	4.8
5000 ft (1524 M)				
Full	2/4	7.5	4/4	8.0
Partial	4/4	9.8	4/4	8.0

TABLE 28 RESULTS OF THE ALIGNMENT STUDY – GEOMETRY: LEVEL TO 6% GRADE

	Modified California		Payne No. 7	
	Detection Ratio	Time to Detect	Detection Ratio	Time to Detect
One Lane Blocked				
500 ft (152 M)				
Full	4/4	4.5	4/4	3.8
Partial	4/4	4.8	4/4	4.3
1000 ft (305 M)				
Full	4/4	4.8	4/4	4.5
Partial	4/4	4.8	4/4	5.0
2500 ft (762 M)				
Full	4/4	7.8	4/4	7.3
Partial	4/4	8.0	3/4	6.3
5000 ft (1524 M)				
Full	2/4	8.0	2/4	7.5
Partial	2/4	8.0	2/4	7.5
Two Lanes Blocked				
500 ft (152 M)				
Full	4/4	2.8	4/4	2.5
Partial	4/4	2.8	4/4	2.3
1000 ft (305 M)				
Full	4/4	3.3	4/4	3.3
Partial	4/4	4.8	4/4	4.0
2500 ft (762 M)				
Full	4/4	6.3	4/4	4.8
Partial	4/4	5.8	4/4	5.0
5000 ft (1524 M)				
Full	3/4	7.7	4/4	7.8
Partial	4/4	8.5	4/4	8.0

Alignment Section Conclusions

Although changes in alignment affect the values of time to detect and detection ratio, none of the trends evidenced in the earlier studies are upset. Therefore, a station spacing of between 1000 feet (305 M) and 2500 feet (762 M) is indicated. No clear advantage is shown by either the full or partial sensor configuration at a given station.

It is likely that the effectiveness of the incident detection algorithms could be improved by optimization of their detection thresholds based on critical geometric features occurring in freeway sections. Further analysis is required in this area of incident detection algorithm optimization.

CHAPTER 4

COST EFFECTIVENESS ANALYSIS

The results presented in Chapter 3 indicate that freeway sensors should be separated by a distance of between 1000 and 2500 feet (305 and 762 M) to achieve the most effective incident detection algorithm performance. More definitive information on optimum sensor spacing can be obtained if cost is introduced into the evaluation process. In this chapter, a set of procedures will be developed for assisting the user in determining the optimum spacing given: the geometric features of the roadway, the available budget, and the requirements for incident detection algorithm performance as measured by detection ratio and the time to detect an incident. The matter of whether a full or partial lane instrumentation should be used at a given sensor station will also be resolved.

4.1 COSTING PROCEDURES

In this section, a sensor configuration costing procedure, which should be applicable regardless of the user's locality, will be presented. This procedure is designed to be independent of the variables that affect the cost such as inflation rate, discount rate, and differences in the price charged by various vendors for equipment.

Categories of Equipment

The first step is to divide the cost associated with the equipment required for sensor systems into three general categories:

I Items of equipment where cost is directly dependent on the number of sensors

II Items of equipment where cost is directly dependent on the number of stations, and

III Items of equipment where cost is dependent on the overall system and not on numbers of stations and sensors.

Equipment in category I includes the sensors themselves, while category II includes the electronics associated with each station. Category III includes central computers which are used to process

the sensor data. There are some types of equipment that can be associated with either category II or III, depending on the specific type of installation. Examples here are communication and power lines. The California Department of Transportation considers these lines to be system dependent (category III) while agencies in other localities consider them to be station dependent (category II). By retaining these three general categories, any using agency will be able to assign the appropriate category to each item of equipment in accordance with the characteristics of the system under consideration.

Since category III equipment is, by definition, independent of sensor placement, <u>the cost data to be used in this cost effectiveness analysis will be limited to equipment in categories I and II.</u>

The Concept of Normalized Capital Cost

For purposes of specifying costing procedures, the following definitions are helpful:

C_I = total capital costs (including installation) of category I equipment on a per sensor basis (e.g. the sensors themselves)

C_{II} = total capital costs (including installation) of category II equipment on a per station basis (e.g., station electronics and cost of tunneling for sensor emplacements)

R_i = annual interest rate for category i = I, II

m_i = percentage of capital costs allocated to yearly maintenance for category i = I, II

n_i = lifetime (in years) for category i = I, II

S = number of stations per 5000 feet (1524 M) of freeway

D = number of sensors per station

Note that in the treatment presented below, costs will be given in units per 5000 feet (1524 M) of freeway since this is the largest spacing between stations that was simulated. The smaller spacings of 2500, 1000, and 500 feet (762, 305 and 152 M, respectively) are all evenly divisible into the 5000 foot unit.

A measure often used in cost effectiveness analyses is the equivalent annual cost. We define the equivalent annual cost per 5000 feet (1524 M) of freeway for equipment assigned to categories I and II to be:

$$C_A = (S \cdot D \cdot C_I) \left\{ \left[\frac{R_I (1 + R_I)^{n_I}}{(1 + R_I)^{n_I} - 1} \right] + m_I \right\} + (S \cdot C_{II}) \left\{ \left[\frac{R_{II} (1 + R_{II})^{n_{II}}}{(1 + R_{II})^{n_{II}} - 1} \right] + m_{II} \right\} \qquad (2)$$

Unfortunately, there is a severe disadvantage in using this measure. Capital costs, interest rates, lifetime and maintenance costs vary with the national economic situation (e. g., inflation) and also vary from agency to agency because different types of equipment are used. Results could be presented based upon relatively accurate data obtained from a particular agency in the year 1978. This data would not, in general, be valid for other agencies in 1978 or for any agency in the future. Because of these difficulties, it is highly desirable to present costing data in a normalized form that is applicable regardless of local conditions at any time now or in the future.

To do so, let us first define the total capital costs C_c per 5000 feet (1524 M) of freeway for category I and II equipment. Using the previously stated definitions,

$$C_c = S \cdot D \cdot C_I + S \cdot C_{II} \qquad (3)$$

This equation can be rearranged as follows:

$$C_c = C_I \left(S \cdot D + S \cdot \frac{C_{II}}{C_I} \right)$$

Let us now define a <u>normalized capital cost</u> per 5000 feet (1524 M) of freeway as:

$$\overline{C}_c = C_c / C_I = \left(S \cdot D + S \cdot \frac{C_{II}}{C_I} \right) \qquad (4)$$

Note that the unit of normalized cost is the capital cost of category I equipment per sensor. The normalized cost $\overline{C}_c$ is dependent only on S, D, and the cost ratio C_{II}/C_I.

It is possible to convert from normalized capital cost to equivalent annual cost. To illustrate, if the interest rates, maintenance costs and lifetime (in years) are the same for both categories of equipment, i. e., $R_I = R_{II} = R$, $n_I = n_{II} = n$, and $m_I = m_{II} = m$, then

$$C_A = \overline{C}_c C_I \left[\frac{R(1+R)^n}{(1+R)^n - 1} + m \right] \qquad (5)$$

If the three quantities are not equal for both categories of equipment, it is still possible to relate normalized capital cost and equivalent annual cost, but the expression is not as simple.

A Sample Calculation of Normalized Capital Cost and the Conversion to Equivalent Annual Cost

At this point, an illustrative example would probably be helpful to the reader.

Suppose the total capital cost of all equipment dependent on the number of sensors is $400. /sensor, the total capital cost of all equipment dependent on the number of stations is $4000. /station, the annual rate of interest for equipment in both categories is 6%, the percentage

of capital cost allocated for yearly maintenance is 5%, and the lifetime is 10 years. Referring to previously defined notation, this means:

C_I = \$400/sensor $\qquad$ C_{II} = \$4000/station

R = .06 $\qquad$ n = 10 years

m = .05

with the ratio $C_{II}/C_I = 10$.

Now consider the case of a three lane one-directional freeway which is to have a full lane instrumentation and a 1000 foot (305 M) spacing between stations. In other words, the number of stations S per 5000 feet (1524 M) is 5 and the number of sensors per station D is 3. The normalized capital cost $\overline{C}_c$ per 5000 feet (1524 M) of freeway for this configuration with a cost ratio of 10 is

$$\overline{C}_c = S \cdot D + S \cdot \frac{C_{II}}{C_I} = 15 + 50 = 65.$$

From equation (5), the equivalent annual cost per 5000 feet (1524 M) of freeway for category I and II equipment is

$$C_A = 65(400) \left[\frac{.06(1.06)^{10}}{(1.06)^{10} - 1} + .05 \right] = \$4833.$$

If there were 25,000 feet (7620 M) of freeway to be instrumented, the total equivalent annual cost for category I and II equipment would therefore be \$24,165.

4.2 COST EFFECTIVENESS ANALYSIS

Note from equation (4) that the normalized capital cost depends upon two parameters which were variables of the INTRAS simulation study, the number of sensors per station and the number of stations per 5000 feet (1524 M) of freeway, and one parameter which was not,

the cost ratio C_{II}/C_I. Once a value is assumed for this ratio, however, the normalized capital cost for each candidate detector configuration is a fixed quantity. This cost ratio depends upon the specific type of equipment which the user has under consideration. The range of values could conceivably extend from as low as $C_{II}/C_I = 1$ (expensive sensors or very inexpensive station dependent equipment) to possibly a value of 50 (expensive station dependent equipment relative to sensor dependent equipment). In the analysis presented herein, a value of $C_{II}/C_I = 10$ was used, thereby producing the normalized capital cost values shown in Table 29 for each candidate configuration.

Procedures

A cost-effectiveness analysis can now be performed in which the incident detection algorithm effectiveness measure (time to detect or detection ratio) is plotted against the normalized capital cost incurred for each candidate detector configuration providing the input data. Figure 17 shows a prototypical example. The letter F on the plot indicates a full lane configuration at a given station; the letter P a partial configuration. Note that these letters are grouped in pairs which represent spacing between stations. From left to right, these spacings are 5000, 2500, 1000, and 500 feet (1524, 762, 305 and 152 M, respectively) notated as 1, 2, 3, 4 in accordance with the key accompanying the figures. This same notation is used on all subsequent cost-effectiveness plots to indicate sensor spacing.

In the following sub-sections, plots of this type will be presented separately for the mainline, weaving, lane drop/addition, and alignment simulation runs. For each geometric feature, results will be displayed for both of the incident detection algorithms employed in the study. Furthermore, the sensitivity to traffic volume will be investigated by presenting a separate graph in which the detection algorithm effectiveness measure values have been averaged over (1) all simulated volumes, (2) low volume simulations, and (3) high volume simulations. The results have also been averaged over all incident locations.

In no case was a 5000 foot (1524 M) spacing between sensors found to provide a reasonable detection ratio and detection time compared to the other spacings. For this reason, the discussion of results will concentrate on the 500, 1000, and 2500 foot (152, 305, and 762 M) spacings.

TABLE 29 NORMALIZED CAPITAL COST FOR EACH SENSOR CONFIGURATION (C_{II}/C_I = 10)

Configuration	Normalized Capital Cost ($\overline{C}_c$)
<u>Three-lane:</u> full (D=3), partial (D=1)	
500 ft (152 M), S = 10	
Full	130
Partial	110
1000 ft (305 M), S = 5	
Full	65
Partial	55
2500 ft (762 M), S = 2	
Full	26
Partial	22
5000 ft (1524 M), S = 1	
Full	13
Partial	11
<u>Four-lane:</u> full (D=4), partial (D=2)	
500 ft (152 M), S = 10	
Full	140
Partial	120
1000 ft (305 M), S = 5	
Full	70
Partial	60
2500 ft (762 M), S = 2	
Full	28
Partial	24
5000 ft (1524 M), S = 1	
Full	14
Partial	12

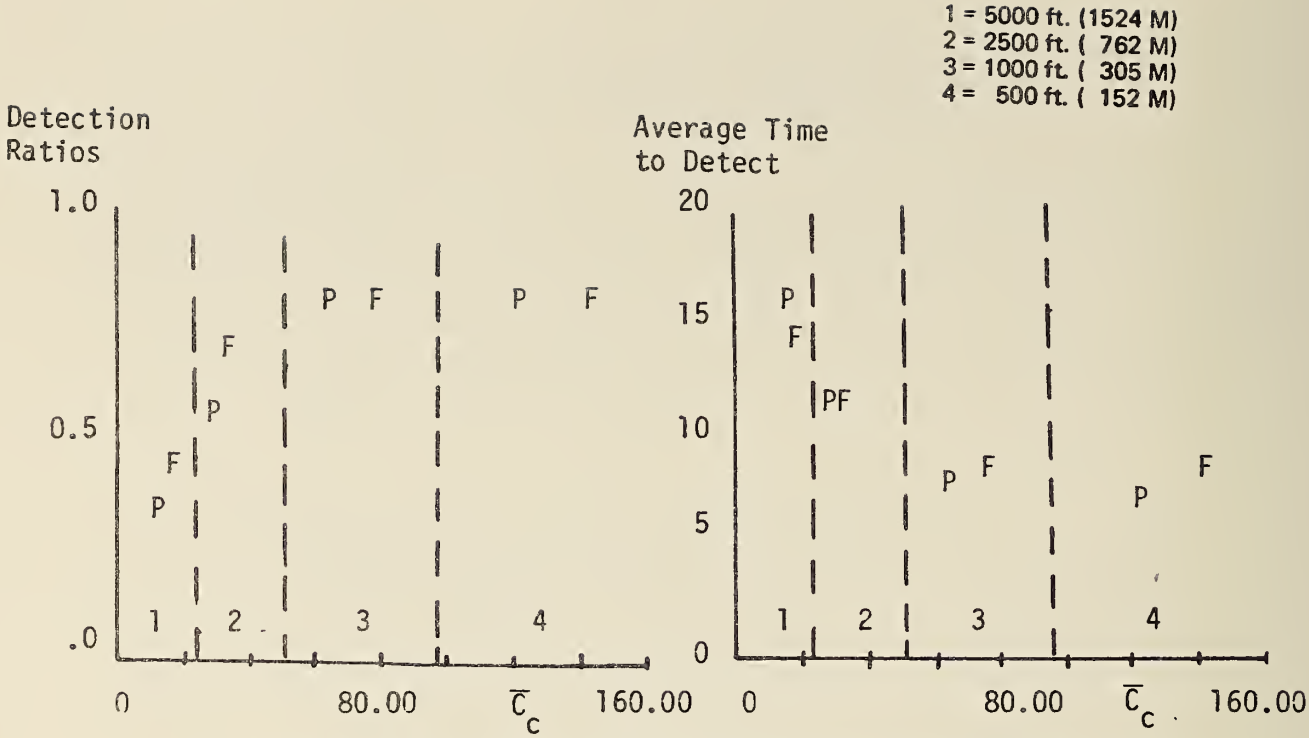


FIGURE 17 EXAMPLE OF COST EFFECTIVENESS PLOTS

Interpretation Guidelines

In any cost effectiveness analysis, an increase in effectiveness is usually accompanied by an increase in cost. This trend certainly occurs frequently in the graphs which follow. In such cases, it is possible to establish some general recommendations. However, the user must make his own specific conclusions on sensor configuration based upon his performance requirements and budget. The graphs will assist by quantifying the percentage increase in detection effectiveness which can be realized by a specific increment in cost expenditure.

In certain cases, a lower cost configuration results in improved performance over a higher cost configuration. More definitive recommendations are provided when this occurs.

The reader is reminded that the normalized capital cost values were fixed throughout the study based upon a cost ratio value of 10. The relationship of detection effectiveness to cost expenditure will vary for other values of C_{II}/C_I. The following simple mechanism will allow the reader to convert the results displayed in the graphs to an alternative cost ratio basis.

For notational convenience, let us define

$$r = C_{II}/C_{I} \qquad (6)$$

and $\overline{C}_c(r)$ as the normalized capital cost for a cost ratio r. Using equation (4), a relationship can be obtained for $\overline{C}_c(r)$ in terms of $\overline{C}_c(10)$, the quantity used in this analysis. This relationship is given by

$$\overline{C}_c(r) = \overline{C}_c(10) \left[(D+r)/(D+10)\right] \equiv \overline{C}_c(10)F. \qquad (7)$$

Note that this relationship is dependent on D, the number of sensors per freeway station. Values of D considered in this effort were: D = 1 (3 lane, partial sensor configuration), D = 2 (4 lane, partial sensor configuration), D = 3 (3 lane, full sensor configuration), and D = 4 (4 lane, full sensor configuration). Figure 18 shows this correction factor F as a function of r for these four values.

Mainline Simulations

Figures 19 and 20 respectively give the cost effectiveness results for the Modified California and Payne number 7 detection algorithms on three lane facilities. For both algorithms, the detection ratio is almost constant for partial and full lane configurations at spacings of 500, 1000, and 2500 feet (152, 305, and 762 M), with a slight degradation at the 2500 foot (762 M) spacing. The time to detect is the same for both the full and partial sensor configurations with a given spacing, and decreases as the spacing decreases. The reduction in detection time as the spacing is decreased from 1000 to 500 feet (305 to 152 M) is relatively small, while the cost roughly doubles.

Because of the small difference in effectiveness between the full and partial configurations, the partial configuration is the most cost effective. Because of the small increase in effectiveness in going from a 1000 foot (305 M) to a 500 foot (152 M) spacing, we conclude that the most cost effective spacing is in the range between 1000 and 2500 feet (305 and 762 M), the value being dependent on the needs and budget of the user.

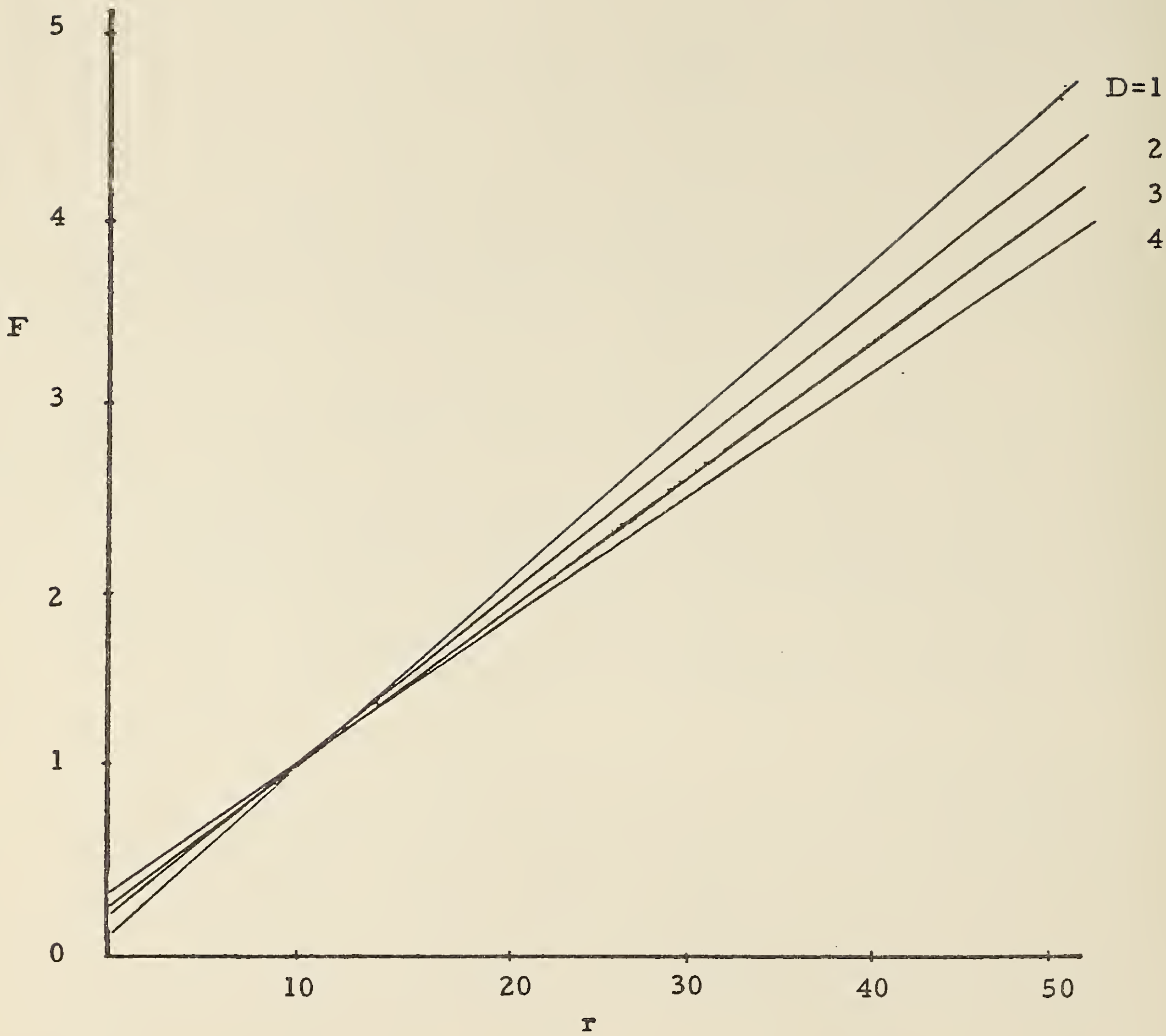
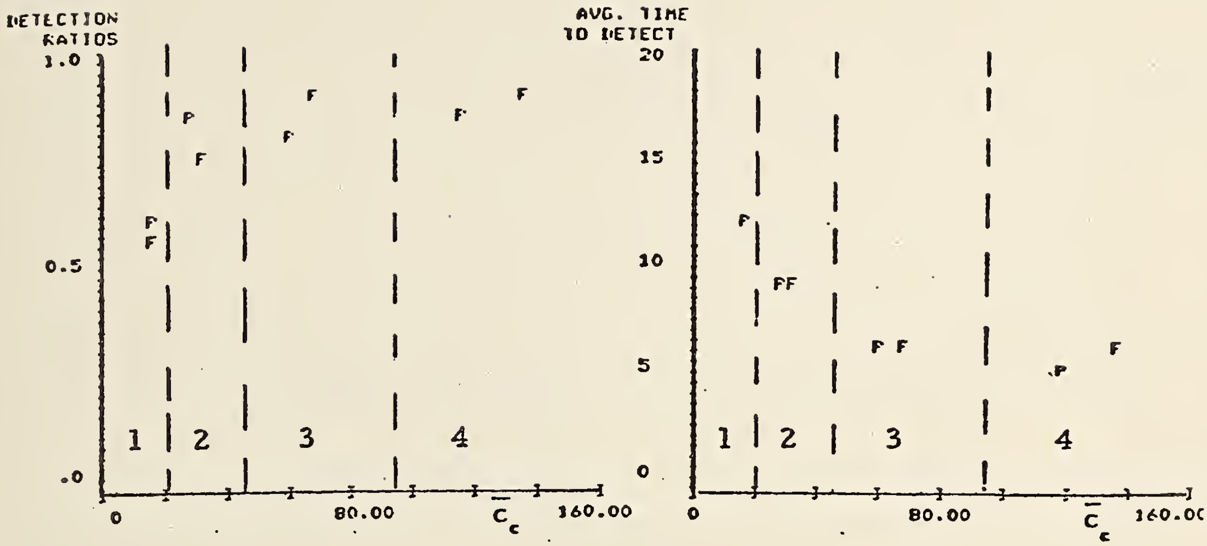
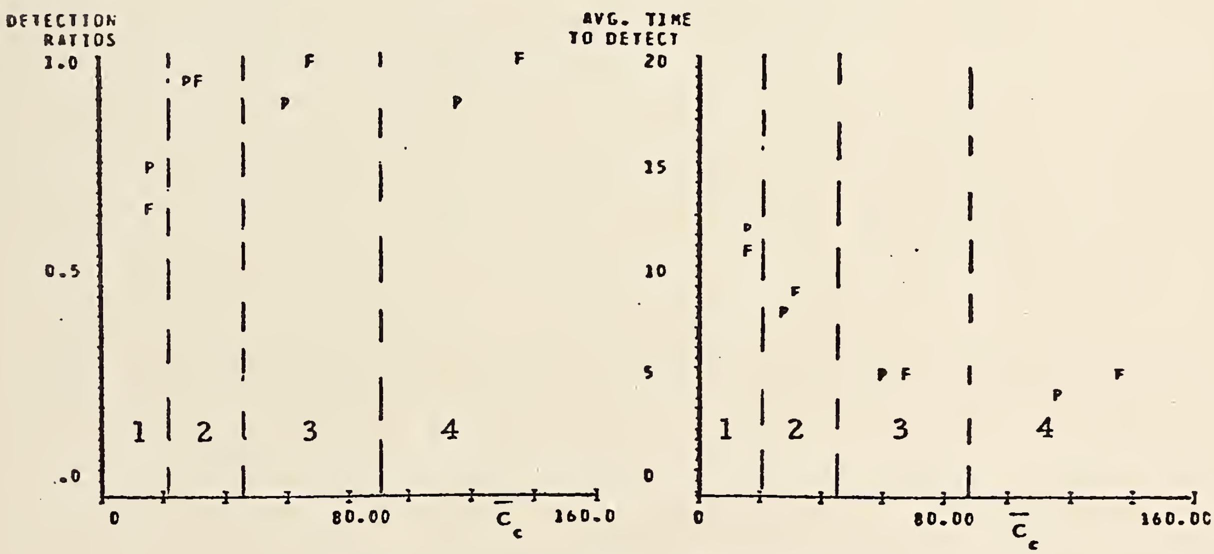


FIGURE 18 CORRECTION FACTOR $F = (D + r)/(D + 10)$ VERSUS r FOR CONVERTING NORMALIZED COST $\overline{C}_c(10)$ WITH COST RATIO $r = 10$ TO NORMALIZED COST WITH OTHER VALUES OF COST RATIO r.



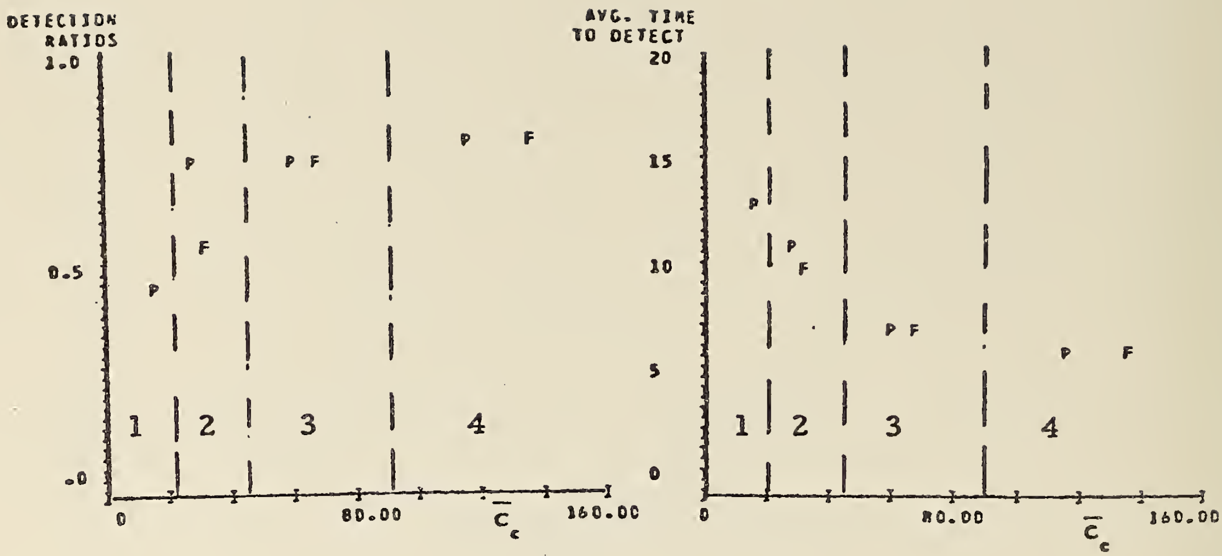
a) Averaged over all volumes



b) High volumes (1500 and 1800 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

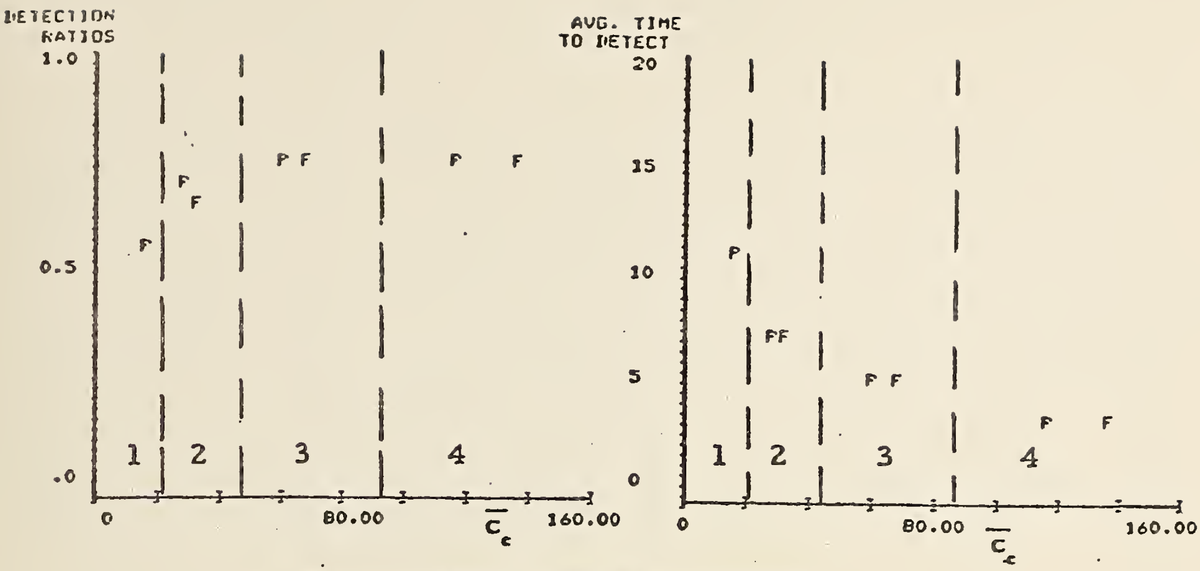
FIGURE 19 COST EFFECTIVENESS PLOTS FOR 3 LANE ONE-DIRECTIONAL MAINLINE SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



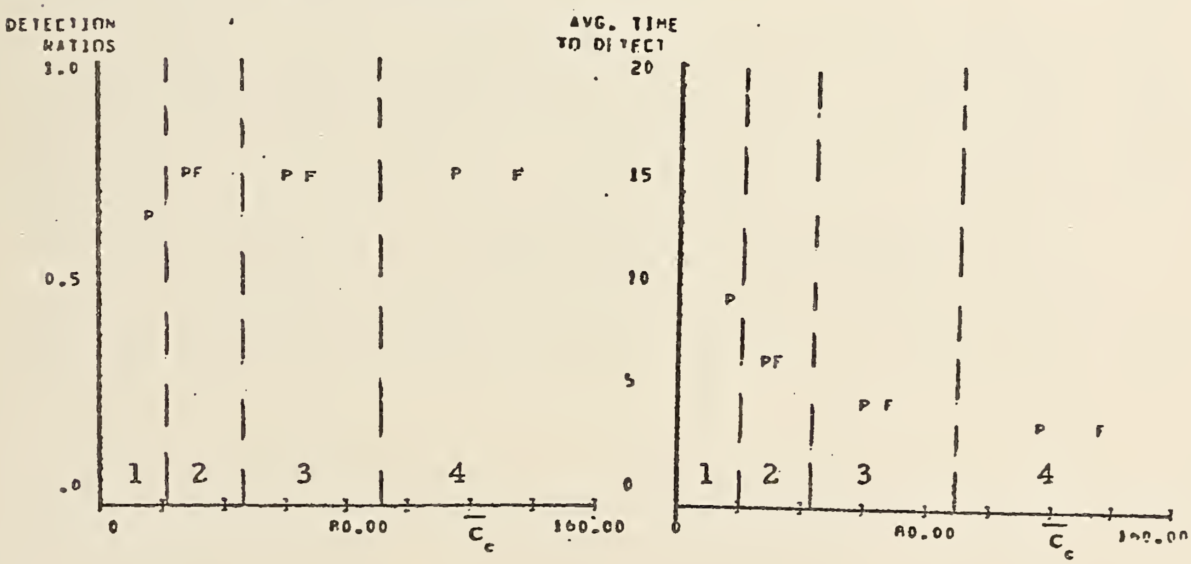
c) Low volumes (1000 and 1300 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 19 CONTINUED



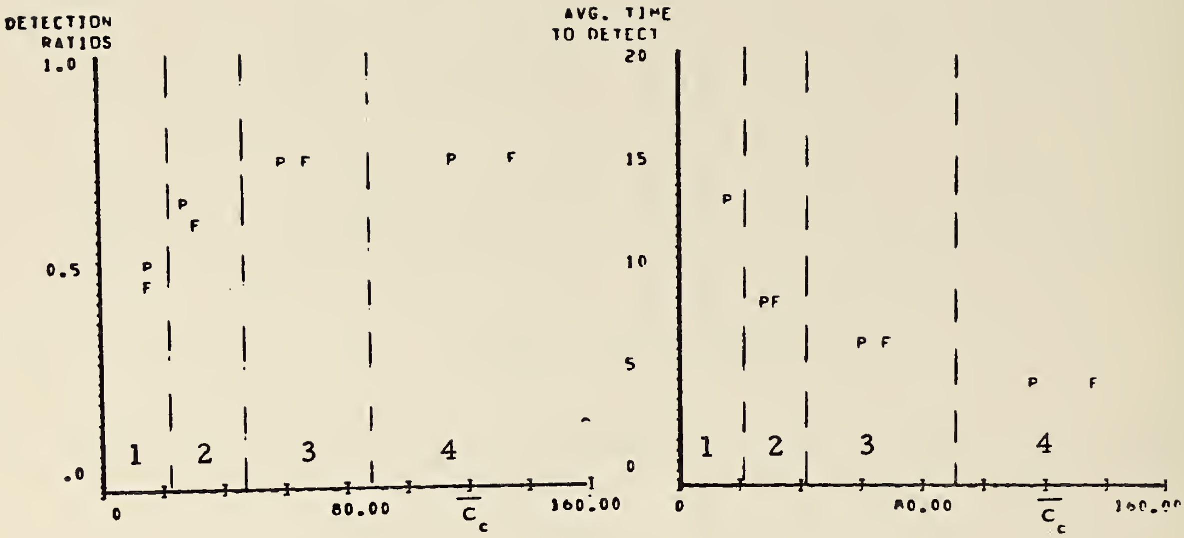
a) Averaged over all volumes



b) High volumes (1500 and 1800 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 20 COST EFFECTIVENESS PLOTS FOR 3 LANE ONE-DIRECTIONAL MAINLINE SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



c) Low volumes (1000 and 1300 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 20 CONTINUED

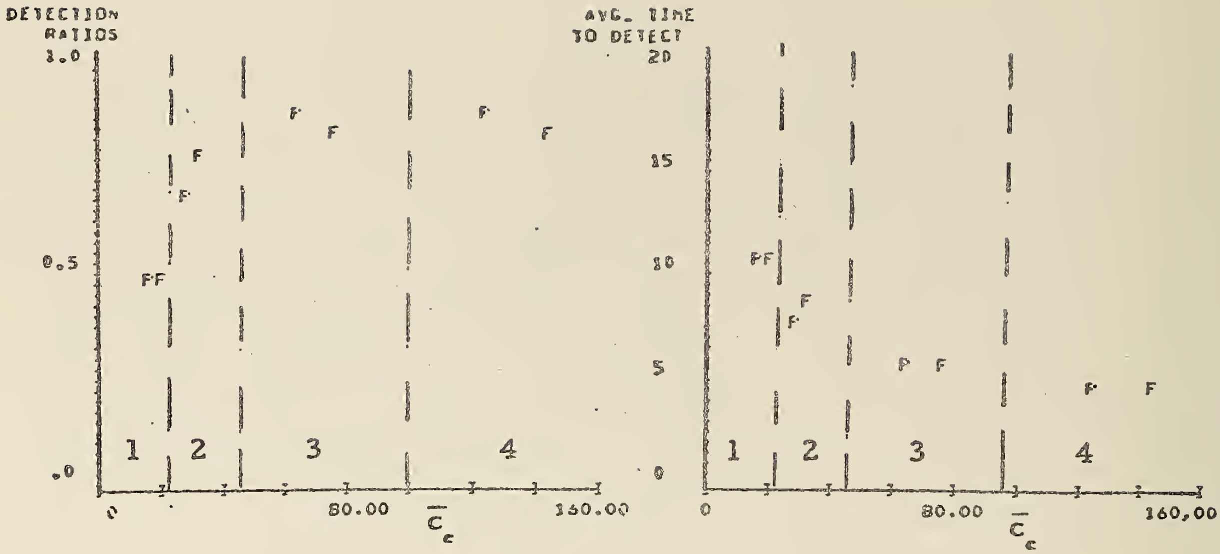
The cost effectiveness results for the four lane case are presented in Figures 21 and 22. With one exception, the effectiveness measures for the 1000 and 500 foot (305 and 152 M) spacings are about equal for both partial and full configurations. The 500 foot (152 M) full configuration operating at high volumes with the Modified California algorithm has a relatively small detection ratio. The 2500 foot (762 M) spacing generally results in lower effectiveness with the exception of the high volume, Modified California algorithm case. As in the three lane case, the most cost effective configuration is the partial. It has a lower cost and its effectiveness is comparable to the full configuration. The best spacing is again in the range from 1000 to 2500 feet (305 to 762 M) depending on the needs and budget of the user.

Weaving Section Simulations

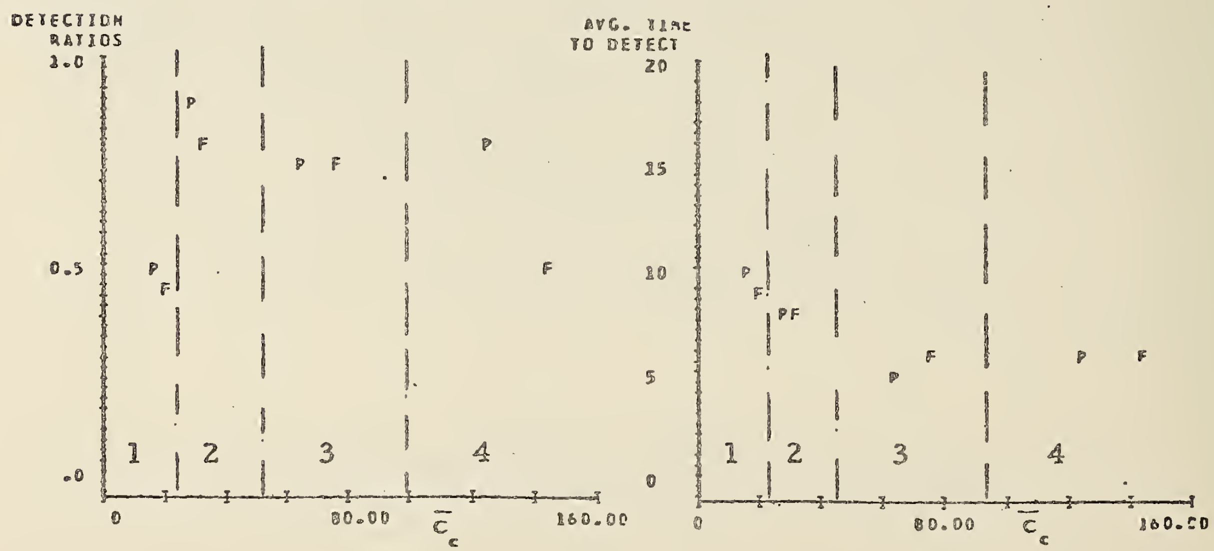
The cost effectiveness plots for the 1000 foot (305 M) weaving section simulations are presented in Figures 23 and 24. The high volume case is 1000 vehicles per hour per lane and the low volume case is 700 vehicles per hour per lane. In comparing the results presented in these two figures, it can be seen that, for spacings of 500 and 1000 feet (152 and 305 M), the full lane configuration is better with the Modified California algorithm and the partial is better with the Payne number 7. Under low volume conditions, the detection ratio drops significantly when the spacing increases to 2500 feet (762 M). The decrease in time to detect in going from 1000 to 500 feet (305 to 152 M) spacings is relatively small.

Because of the relatively large decrease in effectiveness in increasing the spacing from 1000 feet (305 M) to 2500 feet (762 M), and the small increase in effectiveness in decreasing the spacing from 1000 feet (305 M) to 500 feet (152 M), we conclude that the most cost effective spacing is 1000 feet (305 M) for the 1000 foot (305 M) weaving section. No specific recommendation can be made on the choice of partial or full configuration since this is dependent on the incident detection algorithm.

Figures 25 and 26 present the cost effectiveness results for the 2000 foot (610 M) weaving section. Here the high volume case is 1150 vehicles per hour per lane and the low volume case is 850 vehicles per hour per lane. There is little or no increase in effectiveness as the sensor spacing is decreased from 1000 to 500 feet (305 to 152 M), while the detection ratio drops when the spacing is increased to 2500 feet (762 M). There is relatively little difference in effectiveness between the partial and full



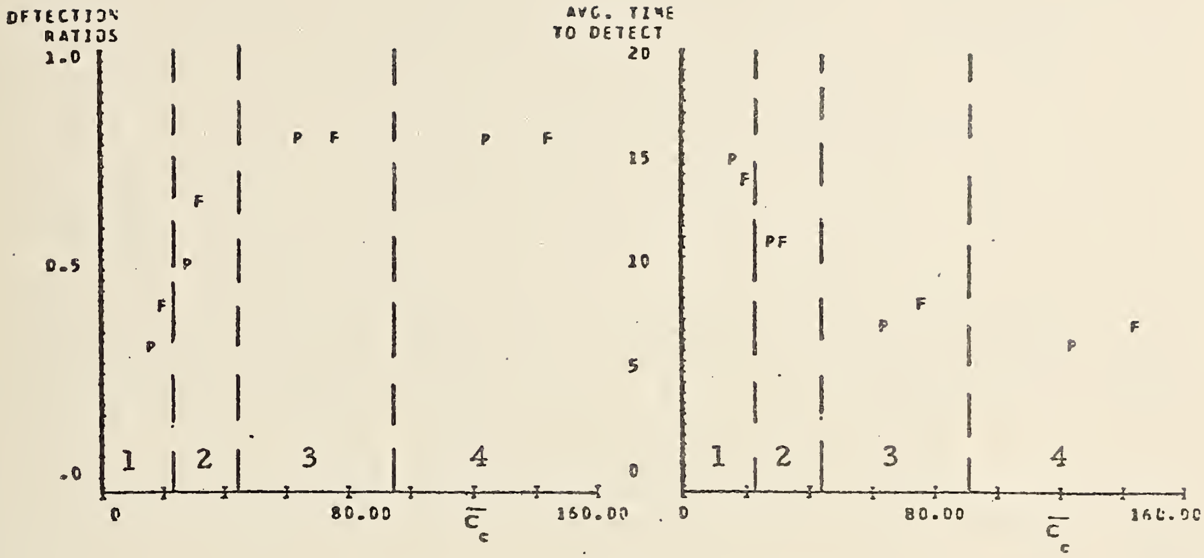
a) Averaged over all volumes



b) High volumes (1500 and 1800 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

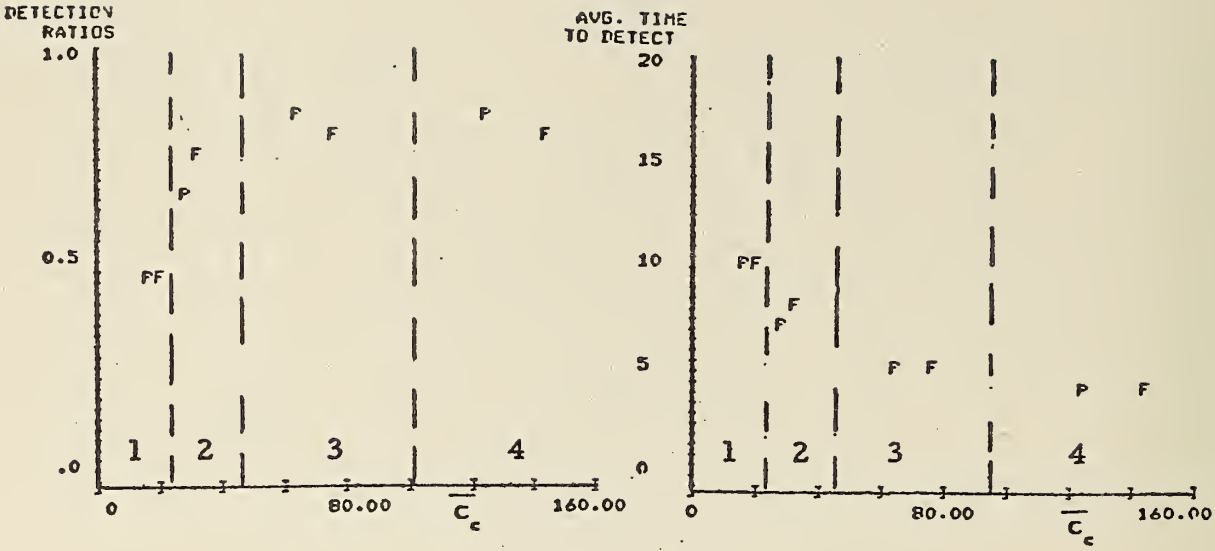
FIGURE 21 COST EFFECTIVENESS PLOTS FOR 4 LANE ONE-DIRECTIONAL MAINLINE SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



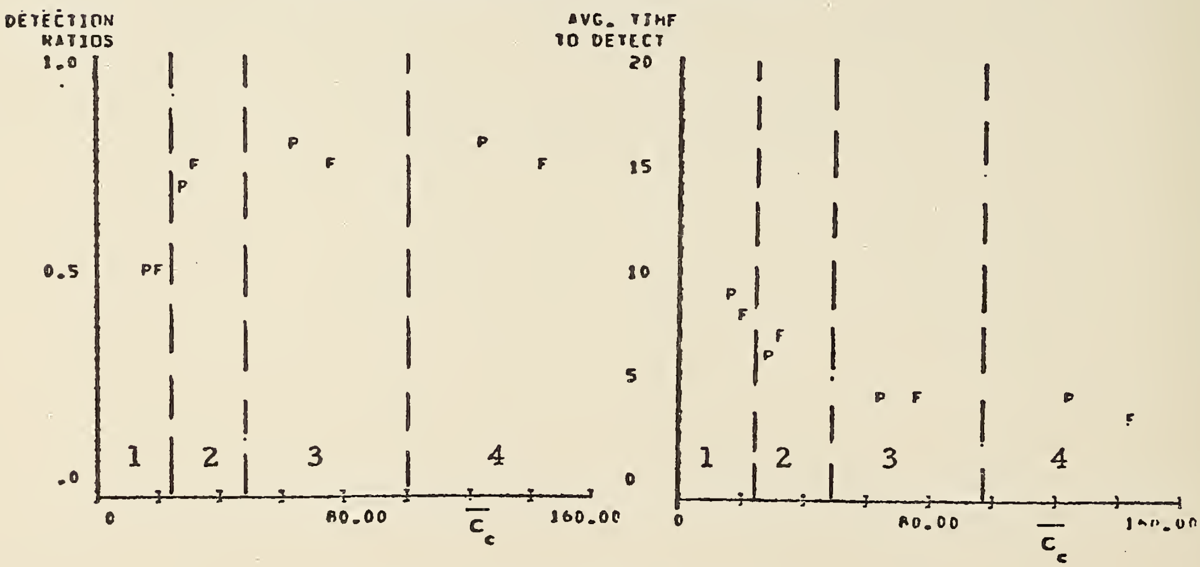
c) Low volumes (1000 and 1300 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 21 CONTINUED



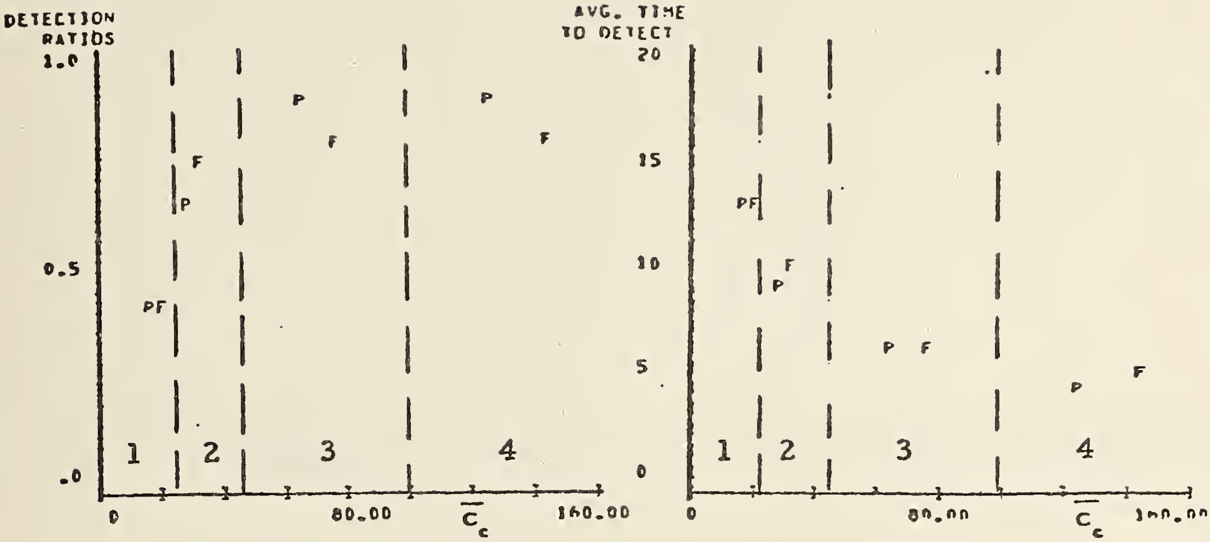
a) Averaged over all volumes



b) High volumes (1500 and 1800 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

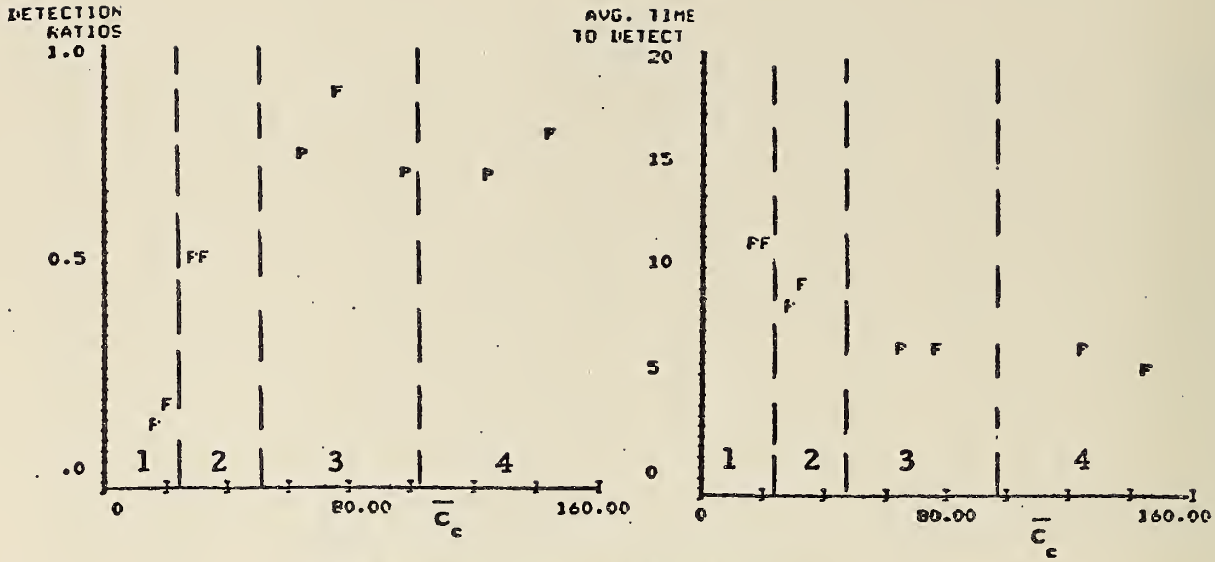
FIGURE 22 COST EFFECTIVENESS PLOTS FOR 4 LANE ONE-DIRECTIONAL MAINLINE SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



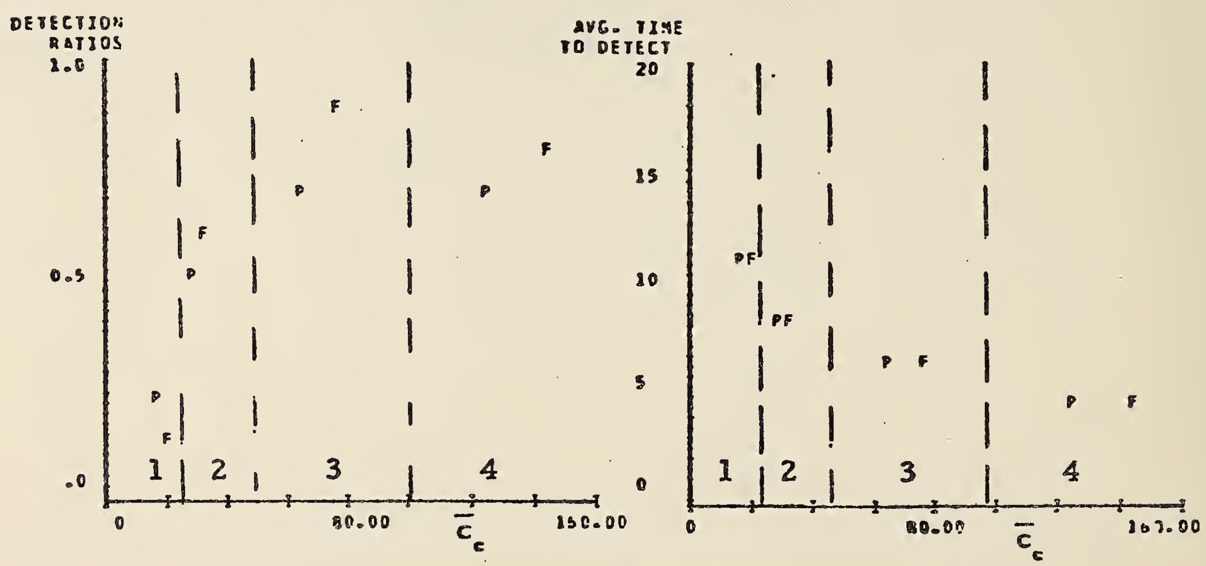
c) Low volumes (1000 and 1300 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 22 CONTINUED



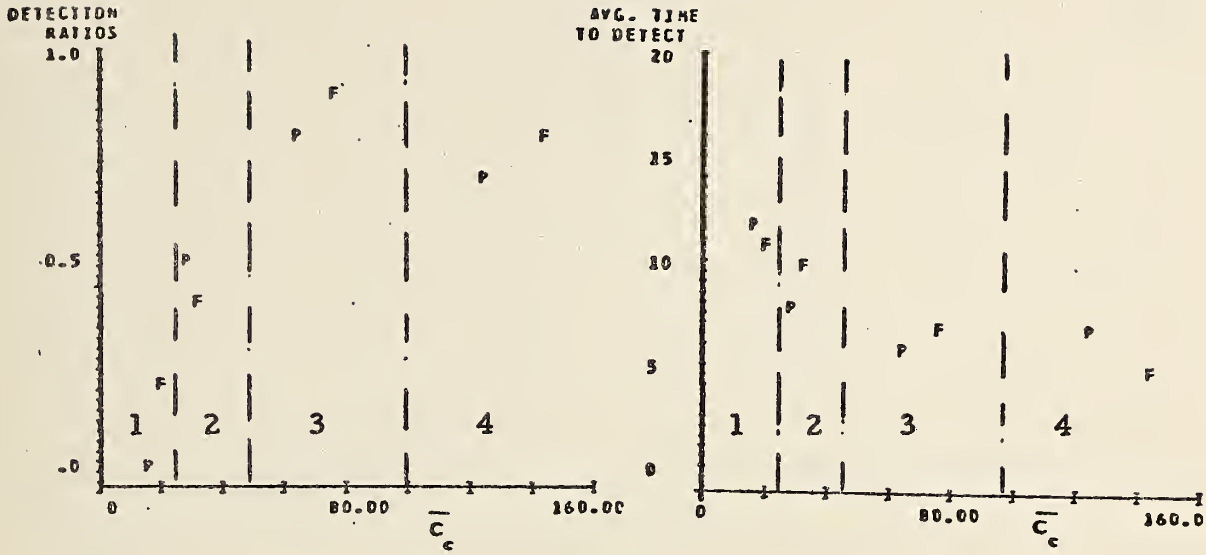
a) Averaged over all volumes



b) High volume (1000 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

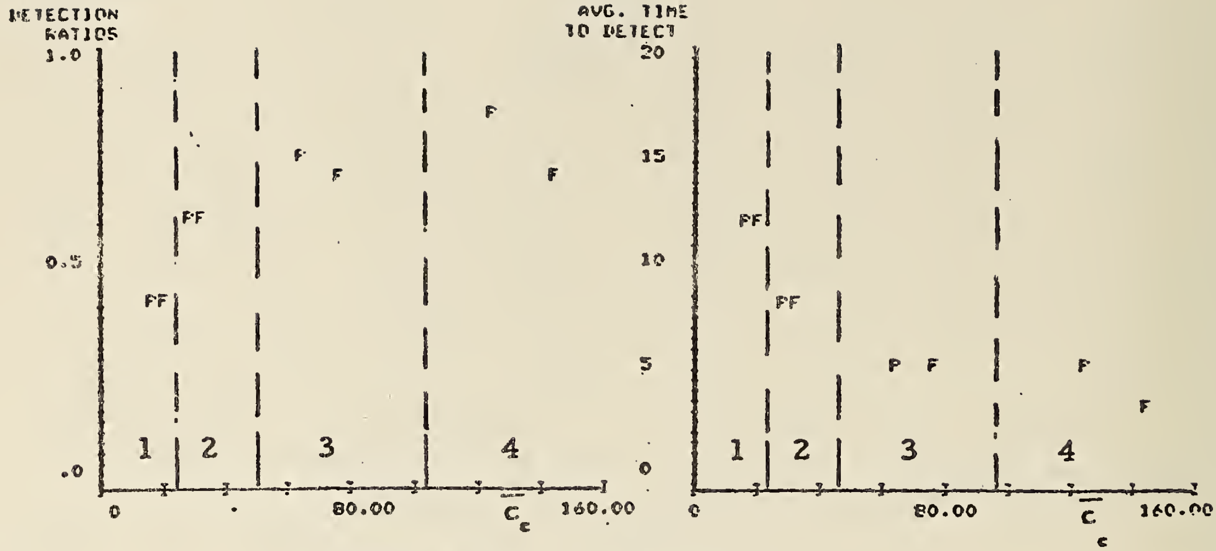
FIGURE 23 COST EFFECTIVENESS PLOTS FOR 1000 FOOT (305 M) WEAVING SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



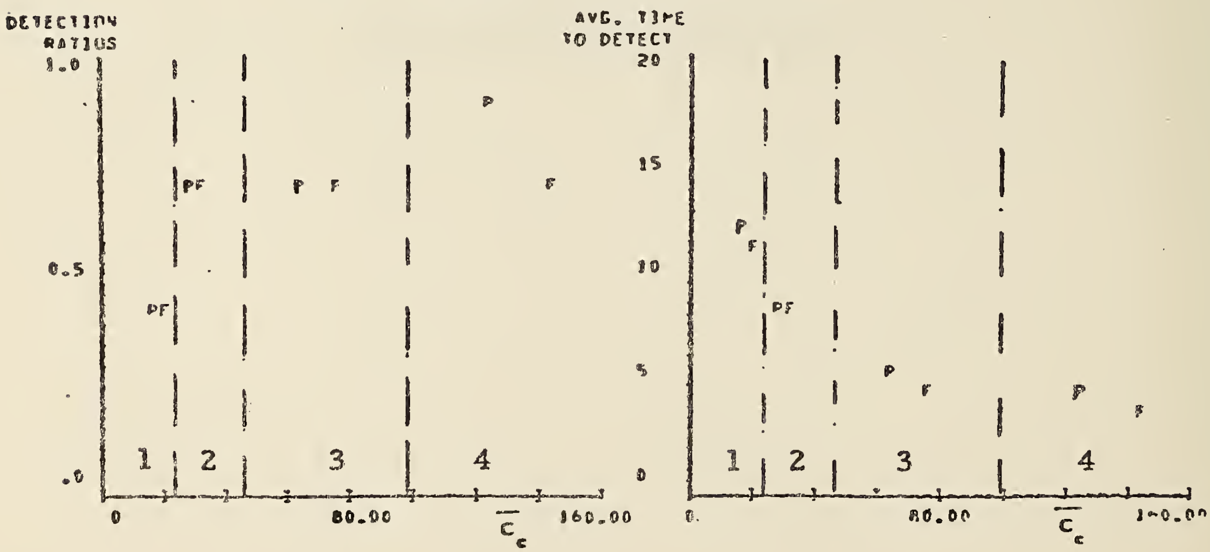
c) Low volume (700 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 23 CONTINUED



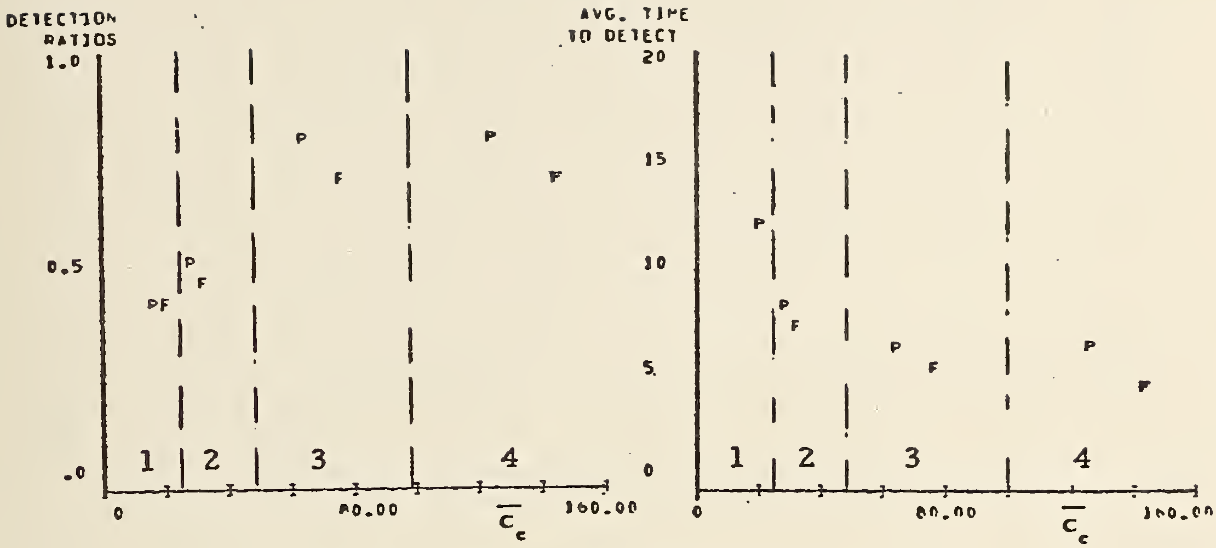
a) Averaged over all volumes



b) High volume (1000 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

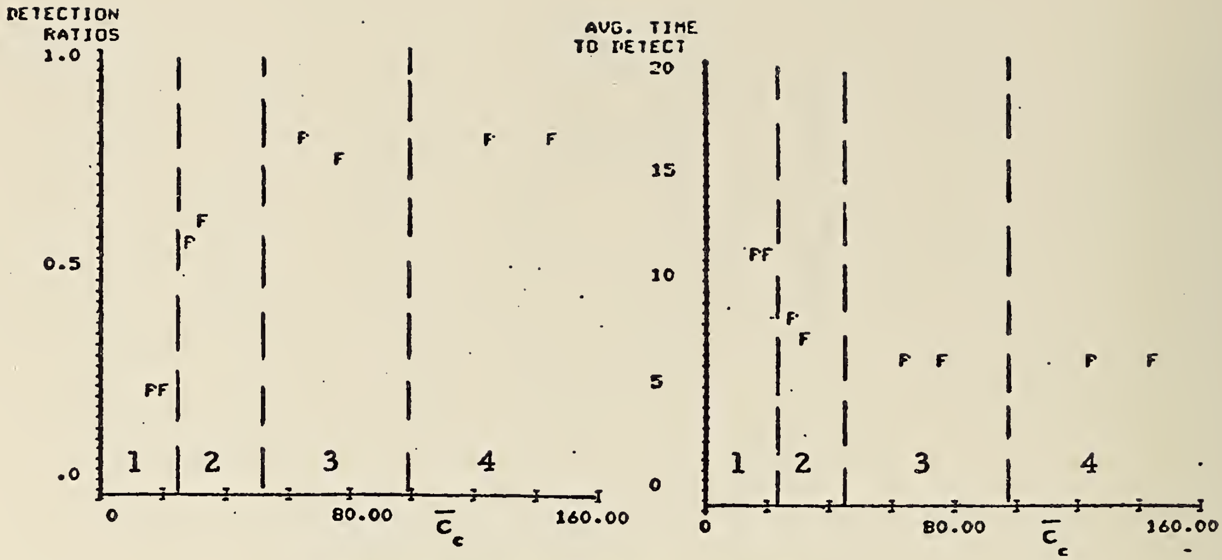
FIGURE 24 COST EFFECTIVENESS PLOTS FOR 1000 FOOT (305 M) WEAVING SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



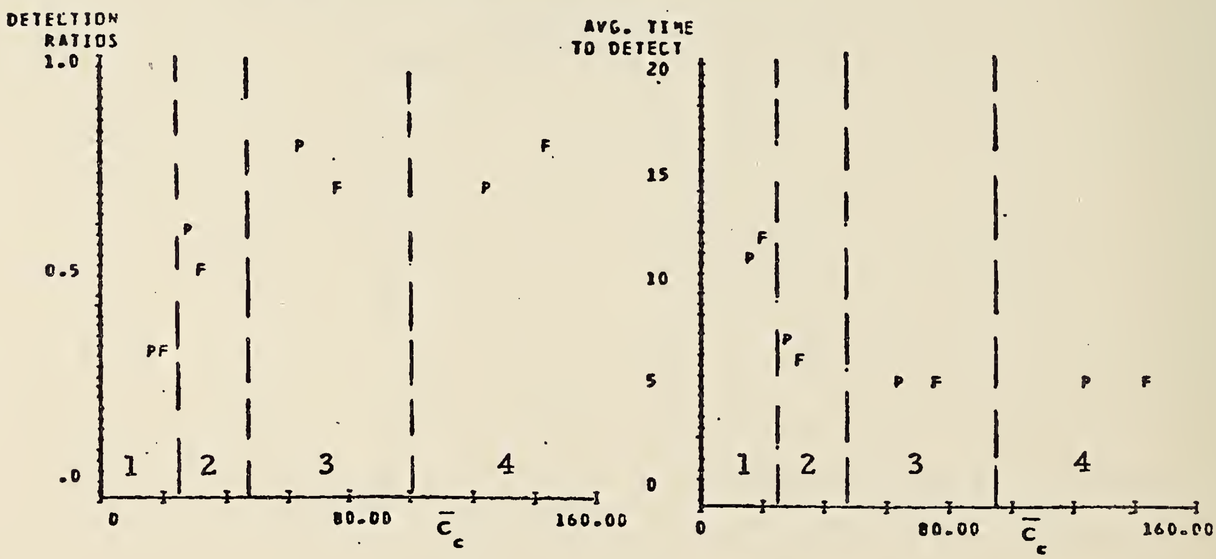
c) Low volume (700 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 24 CONTINUED



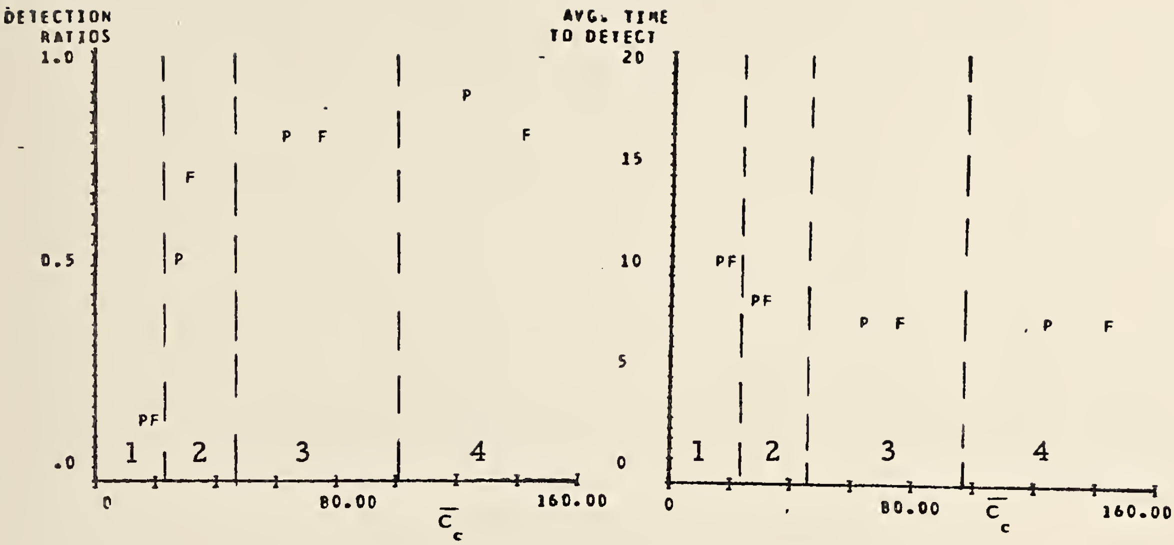
a) Averaged over all volumes



b) High volume (1150 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

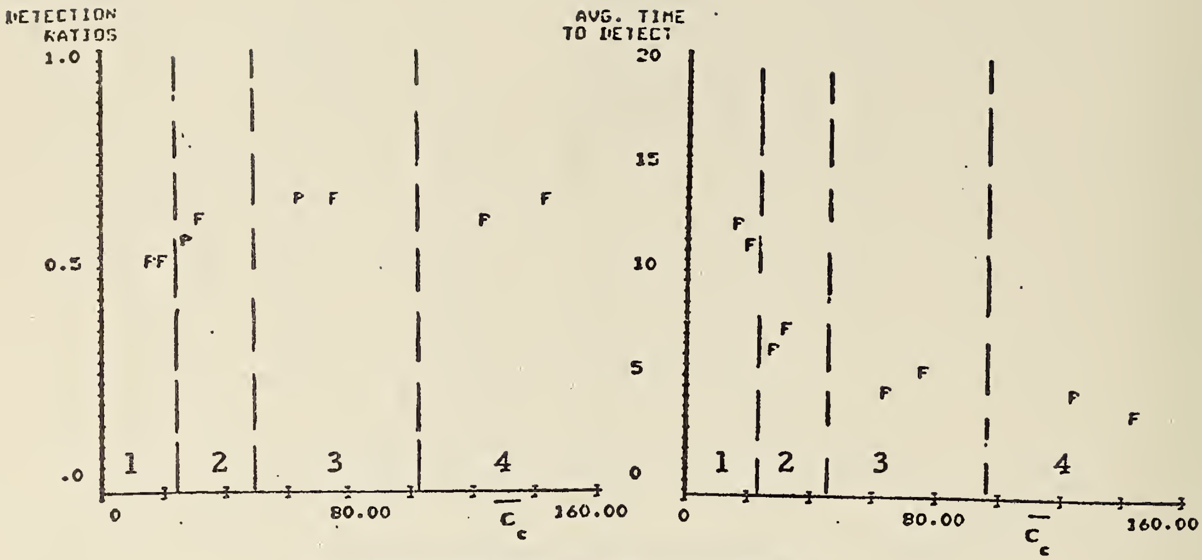
FIGURE 25 COST EFFECTIVENESS PLOTS FOR 2000 FOOT (610 M) WEAVING SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



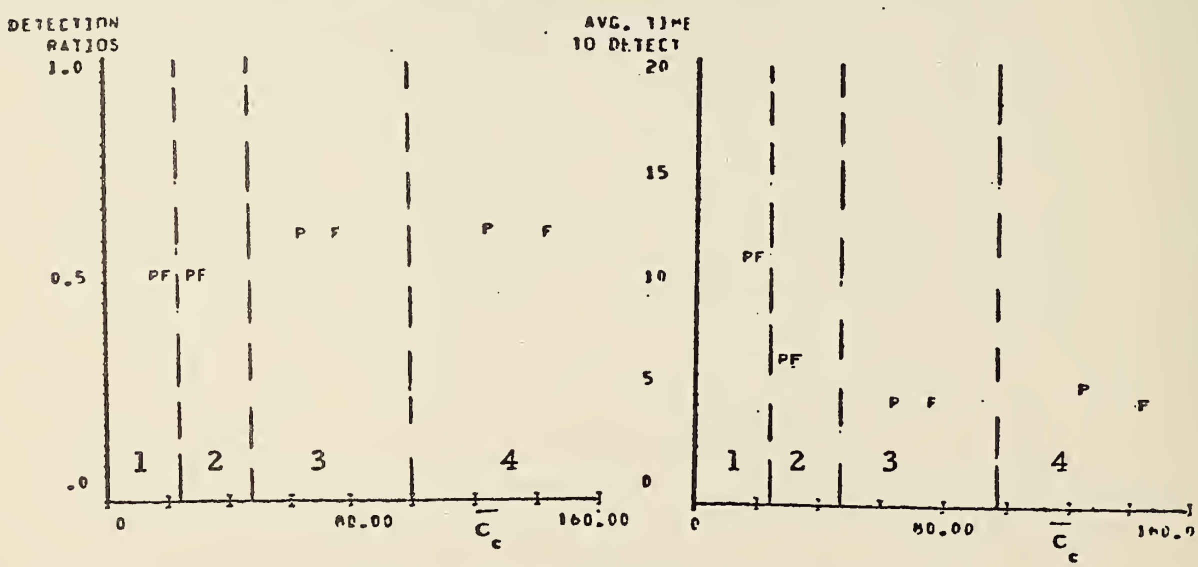
c) Low volume (850 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 25 CONTINUED



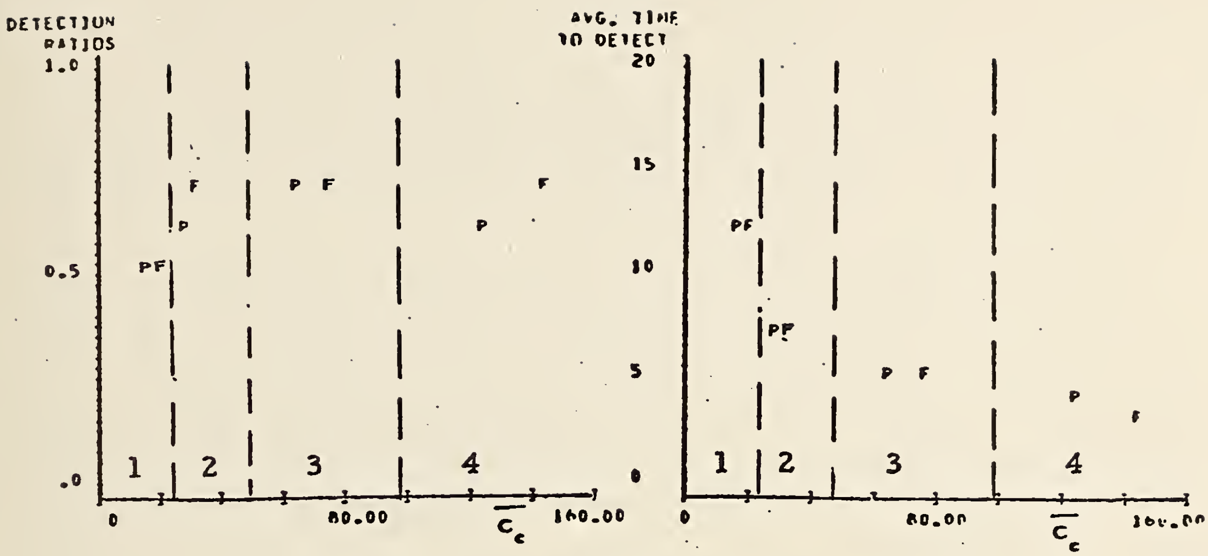
a) Averaged over all volumes



b) High volume (1150 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 26 COST EFFECTIVENESS PLOTS FOR 2000 FOOT (610 M) WEAVING SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



c) Low volume (850 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 26 (CONTINUED)

configurations. The most cost effective spacing for the 2000 foot (610 M) weaving section is, therefore, between 1000 and 2500 feet (305 and 762 M). Because of comparable effectiveness, the partial configuration should be chosen on the basis of cost.

Results for 3000 foot (914 M) weaving section simulations are given in Figures 27 and 28. The low volume traffic flow is 950 vehicles per hour per lane while the high volume flow is 1250 vehicles per hour per lane. For the Payne number 7 detection algorithm, there is little difference in effectiveness between the full and partial configurations. With the Modified California algorithm, however, the partial configuration has a much better detection ratio at high volumes and with 500 foot (152 M) spacings at low traffic volume. For the 1000 and 2500 foot (305 and 762 M) spacings at low traffic volumes, the full configuration is superior. The degradation in effectiveness as the spacing is varied from 1000 to 2500 feet (305 to 762 M) is small. The overall conclusion is that spacings between 1000 feet (305 M) and 2500 feet (762 M) provide the best cost-effectiveness trade-offs.

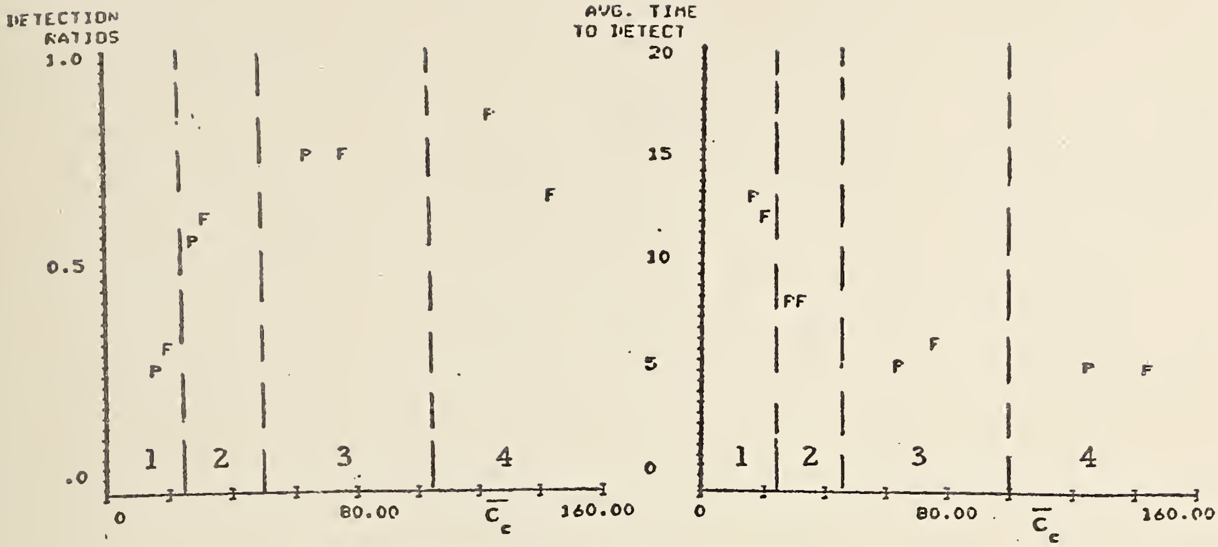
Lane Additions/Lane Drop Simulations

For the lane addition and lane drop simulations, cost effectiveness results will be presented for four traffic volume conditions: average over all volumes, a high total volume of 5400 vehicles per hour, a medium total volume of 4500 vehicles per hour, and a low total volume of 3000 vehicles per hour.

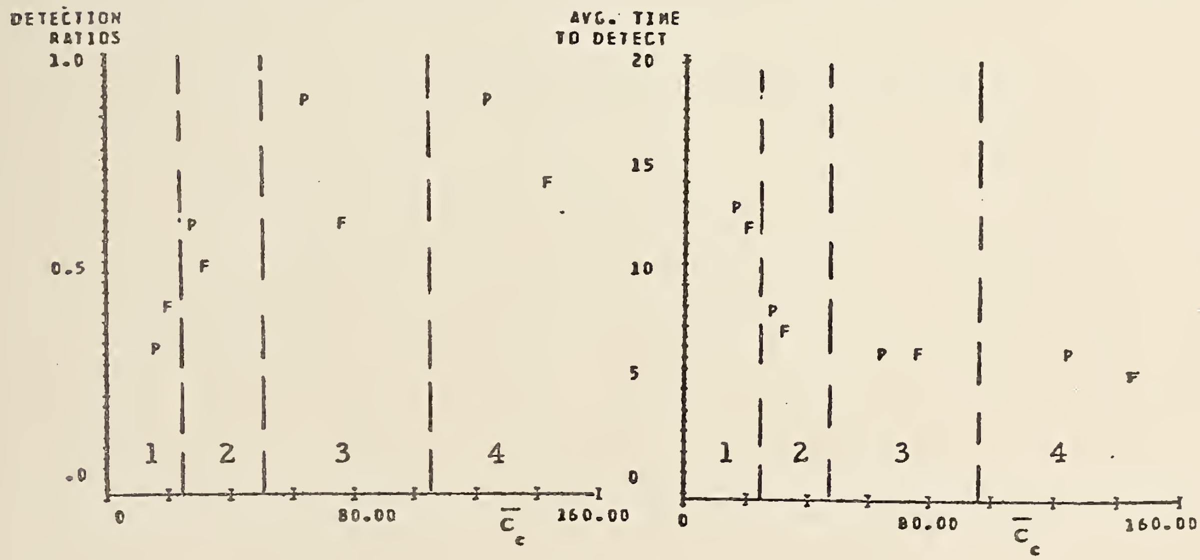
In these simulations, part of the simulated freeway is three lanes and part is four lanes. In order to simplify the presentation of the cost effectiveness results, the costs will be calculated on the basis of a four lane one-directional freeway. This does not affect the conclusions reached on the most cost effective sensor configurations.

Lane Additions

Figures 29 and 30 present the cost effectiveness results for the lane addition simulations. In general, the partial configuration provides a higher detection ratio than the full configuration for all spacings. The detection times are comparable. Note that an increase in sensor spacing from 1000 to 2500 feet (305 to 762 M) results in a considerable decrease in the detection ratio for both algorithms, especially at the low and medium volumes. Decreasing the sensor spacing below 1000 feet (305 M) provides little or no increase in effectiveness.



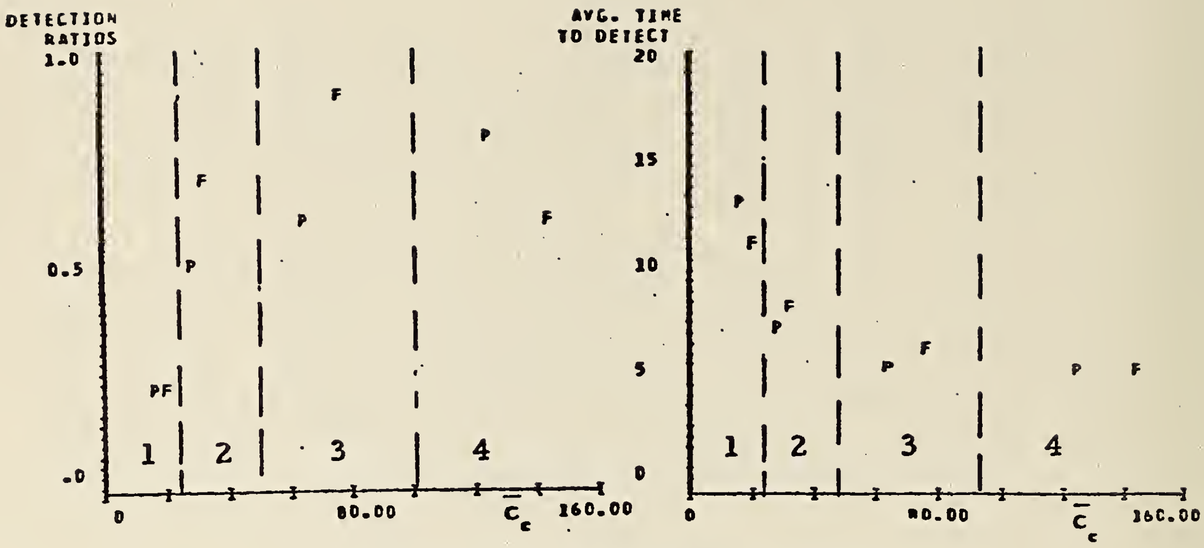
a) Averaged over all volumes



b) High volume (1250 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

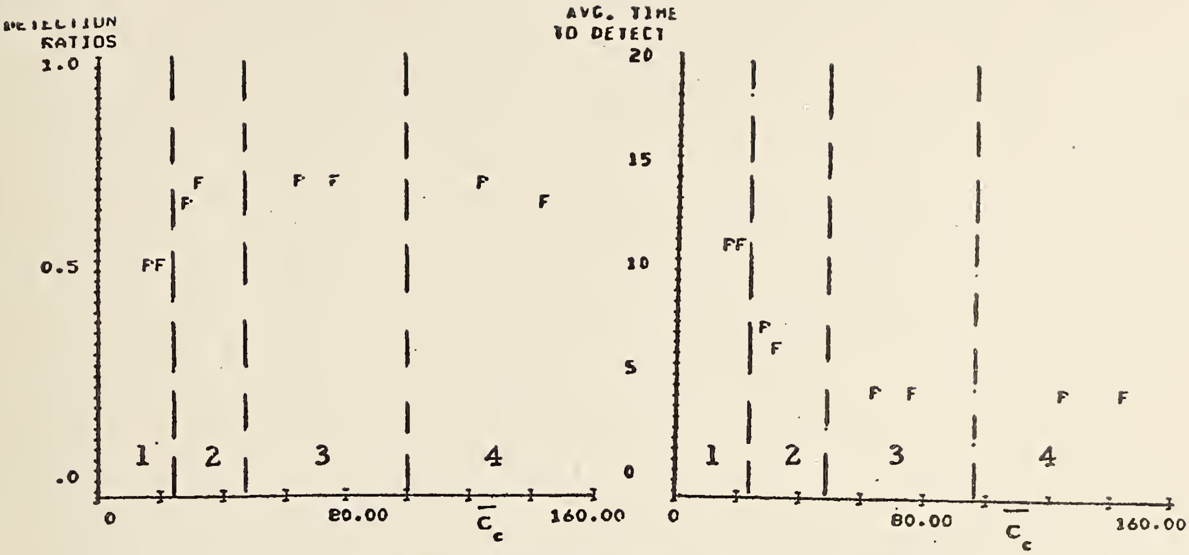
FIGURE 27 COST EFFECTIVENESS PLOTS FOR 3000 FOOT (914 M) WEAVING SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



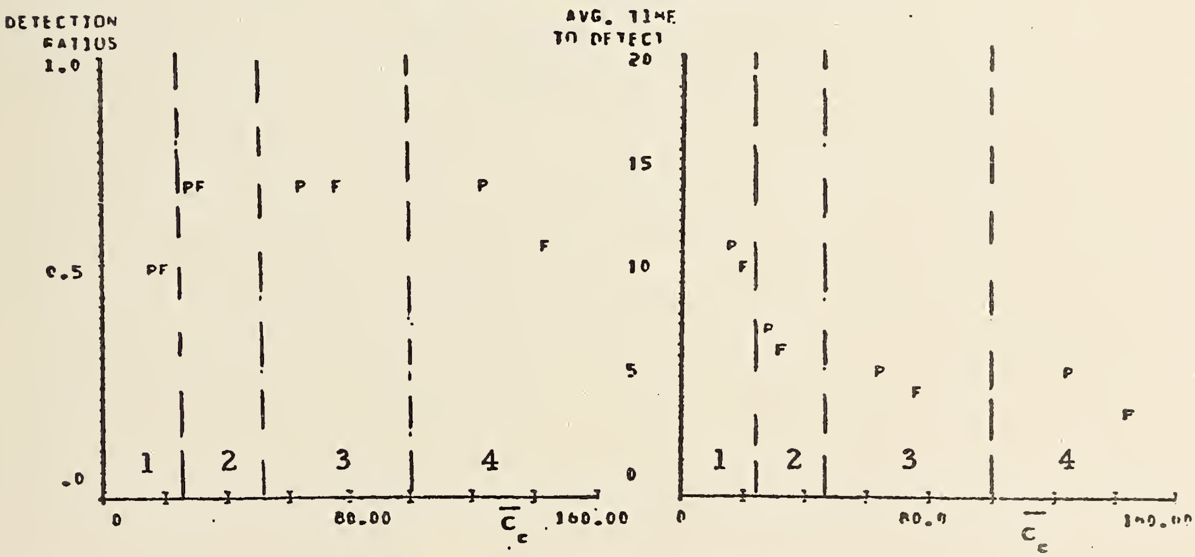
c) Low volume 950 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 27 CONTINUED



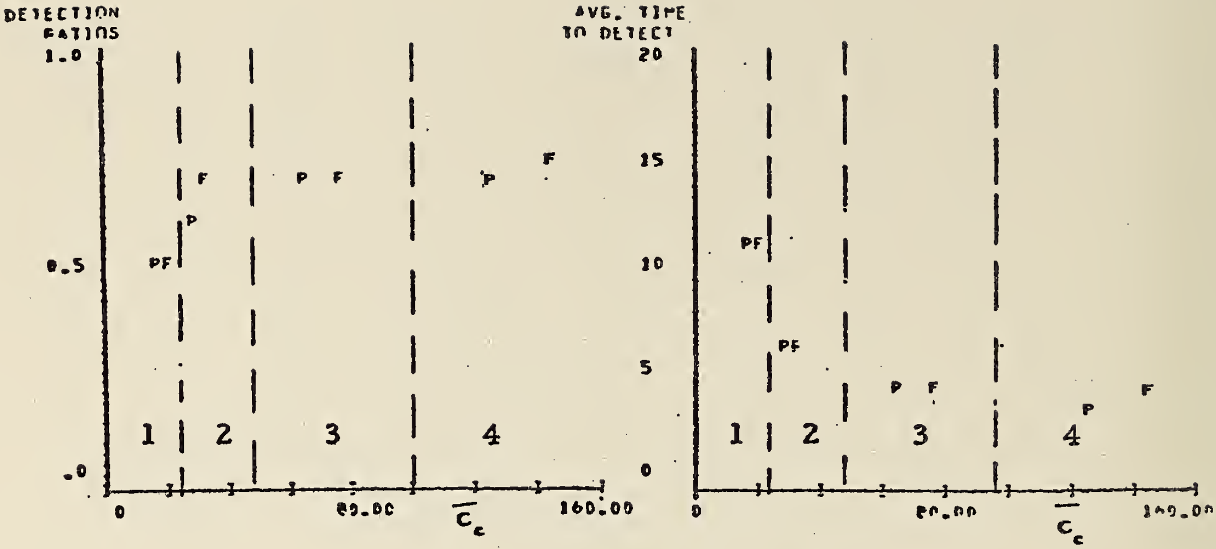
a) Averaged over all volumes



b) High volume (1250 veh/hr/lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

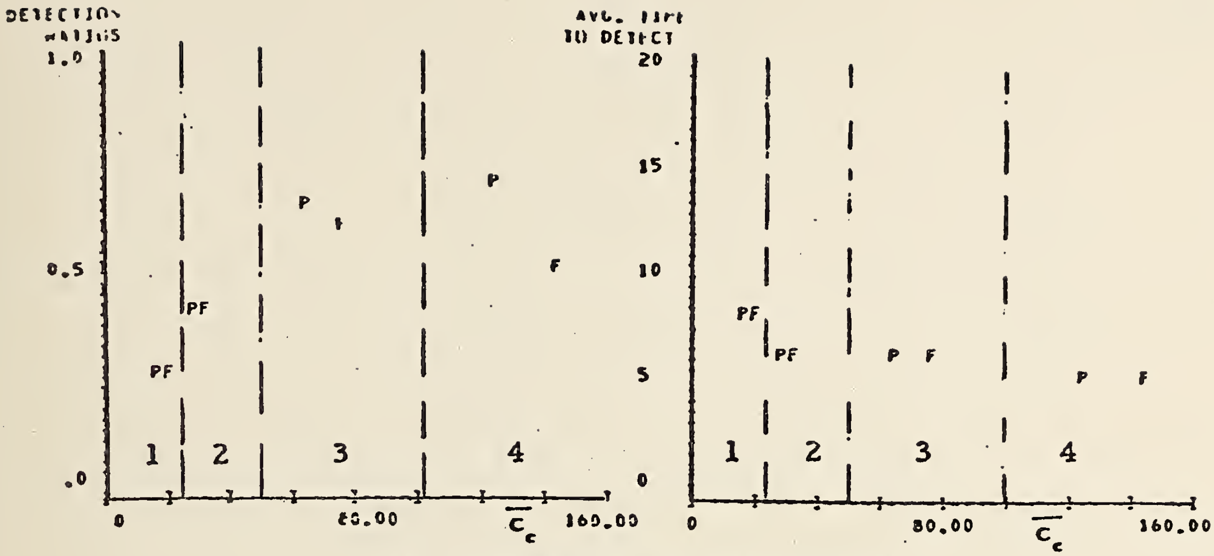
FIGURE 28 COST EFFECTIVENESS PLOTS FOR 3000 FOOT (914 M) WEAVING SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



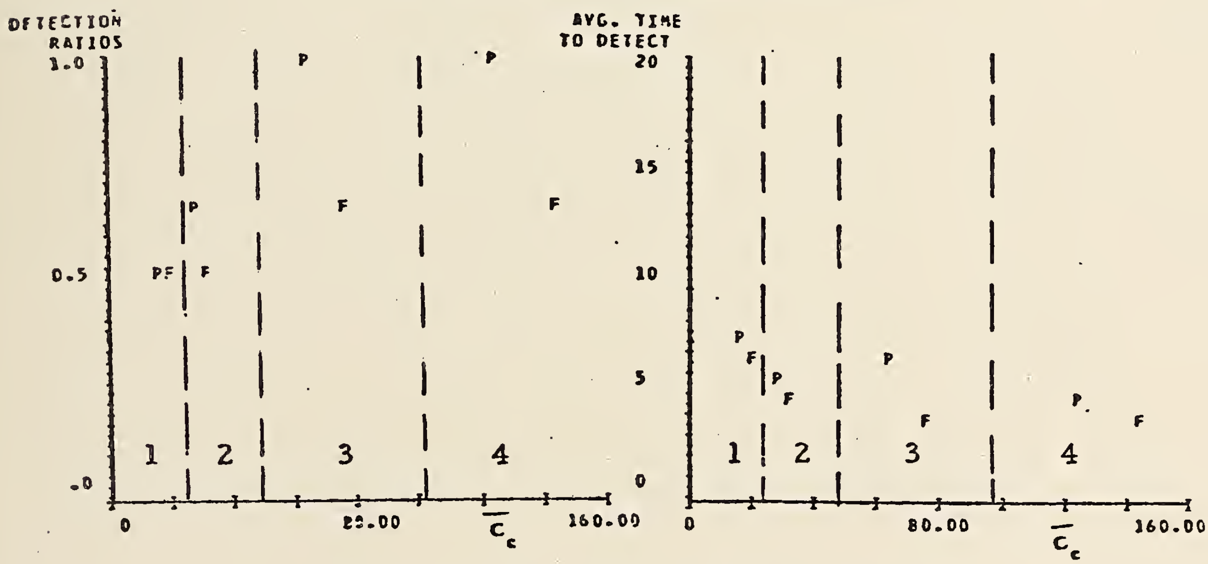
c) Low volume (950 veh/hr/
lane)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 28 CONTINUED



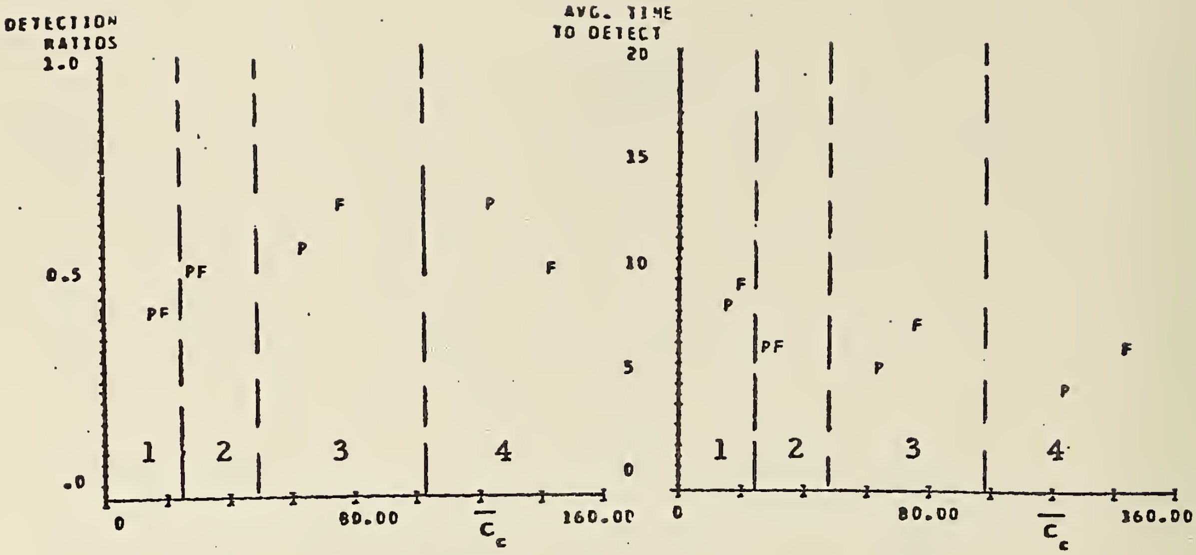
a) Averaged over all volumes



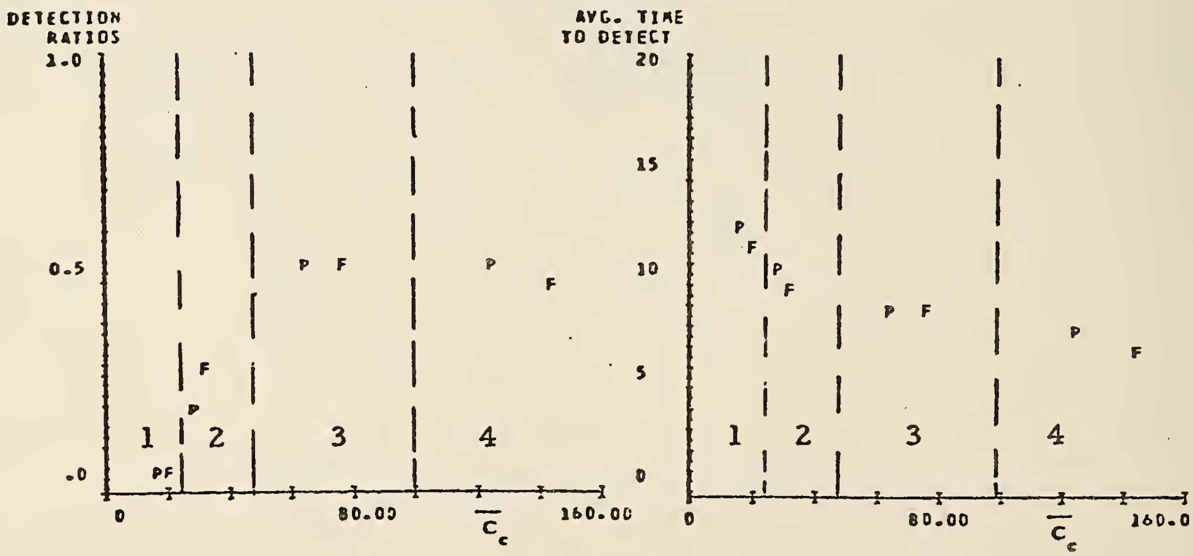
b) High total volume (5400 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 29 COST EFFECTIVENESS PLOTS FOR LANE ADDITION SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



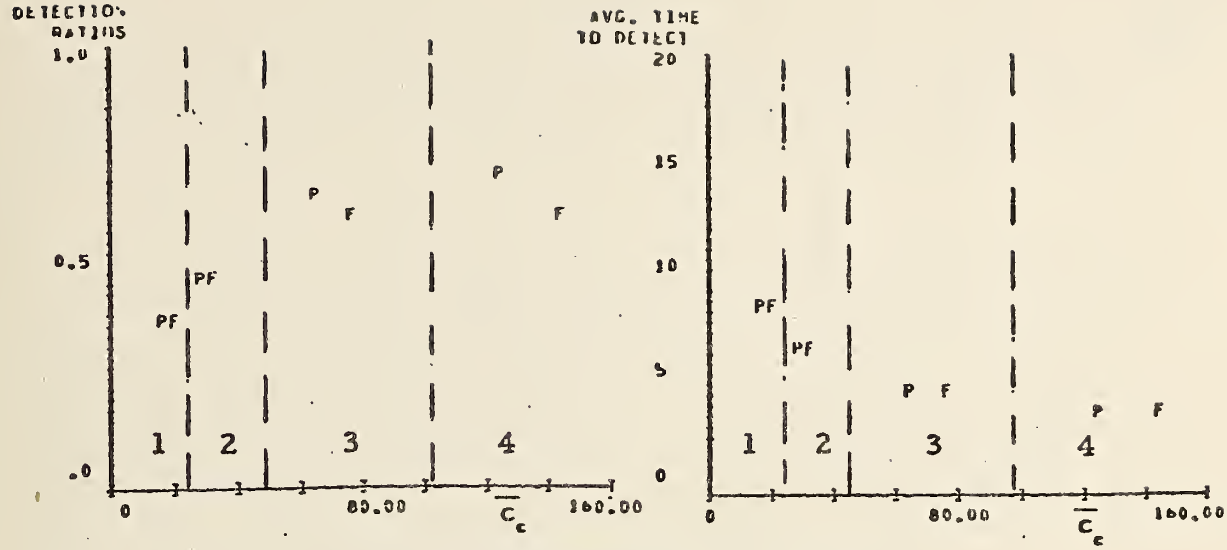
c) Medium total volume (4500 veh/hr)



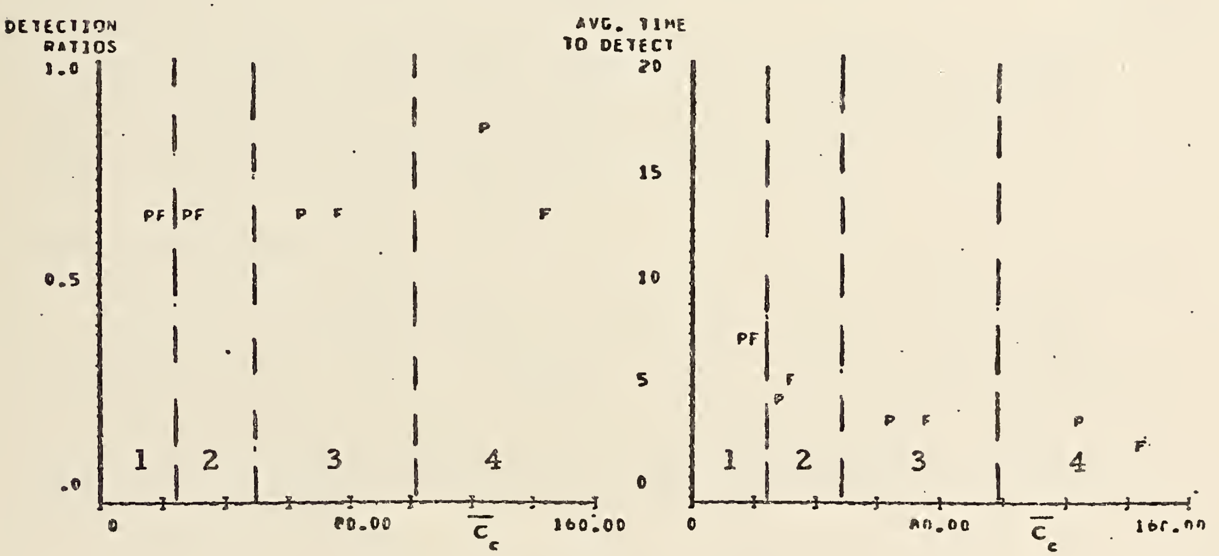
d) Low total volume (3000 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 29 CONTINUED



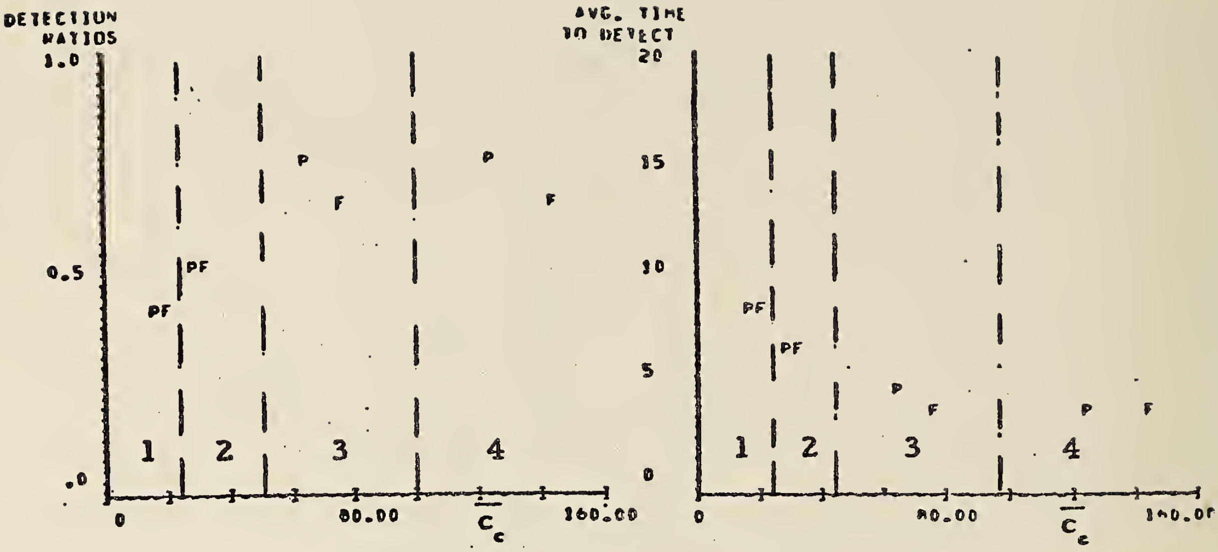
a) Averaged over all volumes



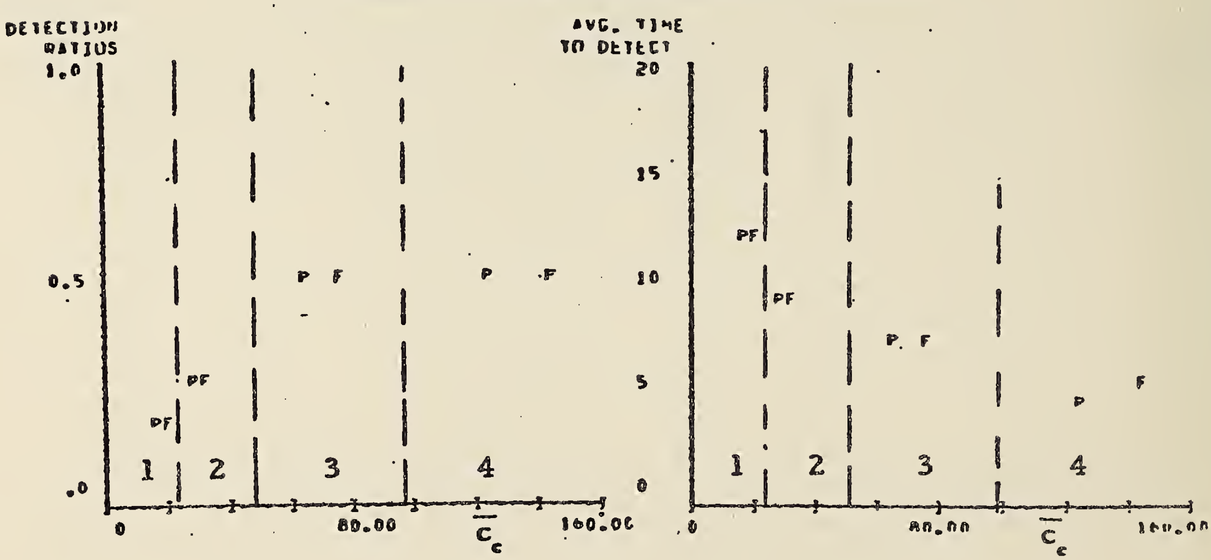
b) High total volume (5400 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 30 COST EFFECTIVENESS PLOTS FOR LANE ADDITION SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



c) Medium total volume (4500 veh/hr)



d) Low total volume (3000 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 30 CONTINUED

These results show that for lane addition situations, the most cost effective sensor placement is a partial configuration with 1000 foot (305 M) spacing.

Lane Drops

The cost effectiveness plots for the lane drop simulations are given in Figures 31 and 32. At 500 and 1000 foot (152 and 305 M) spacings, the effectiveness of the partial lane configuration generally equals or exceeds the detection ratio attained with the full configuration. The 500 foot (152 M) partial configuration has a higher detection ratio than the 1000 foot (305 M) case, whereas the corresponding detection times are comparable. At a 2500 foot (762 M) separation, the full configuration has a better detection ratio than the partial configuration. However, the detection ratio and detection time are worse than with the 1000 foot (305 M) partial configuration.

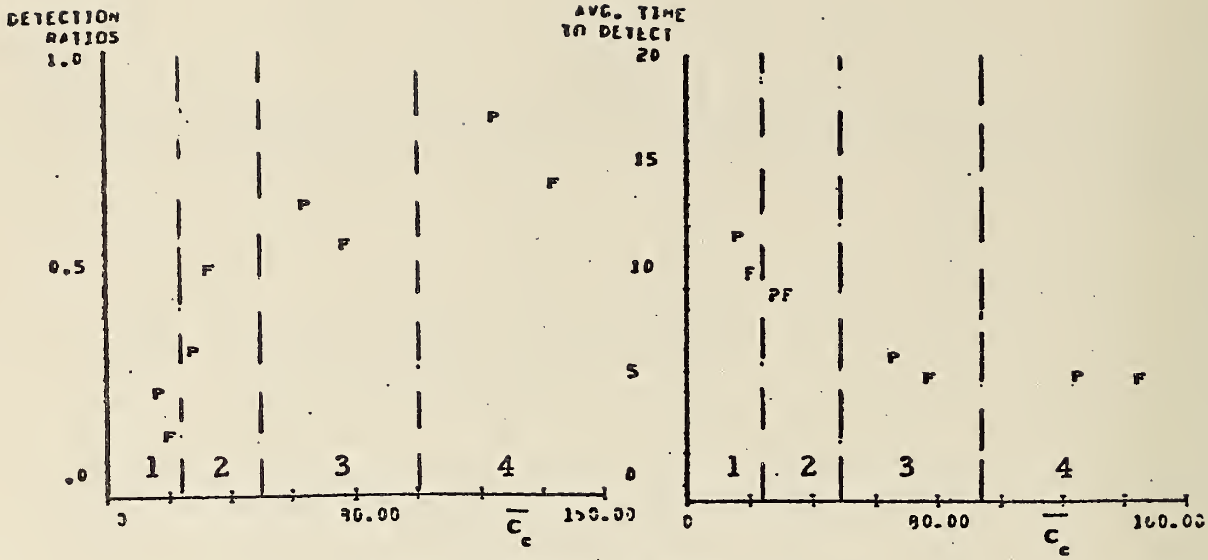
For the lane drop situation, the most cost effective sensor placement is attained by a partial configuration with spacing between 500 and 1000 feet (152 and 305 M). Spacings closer to 500 feet (152 M) provide a better detection ratio, but at a higher cost.

Alignment Simulations

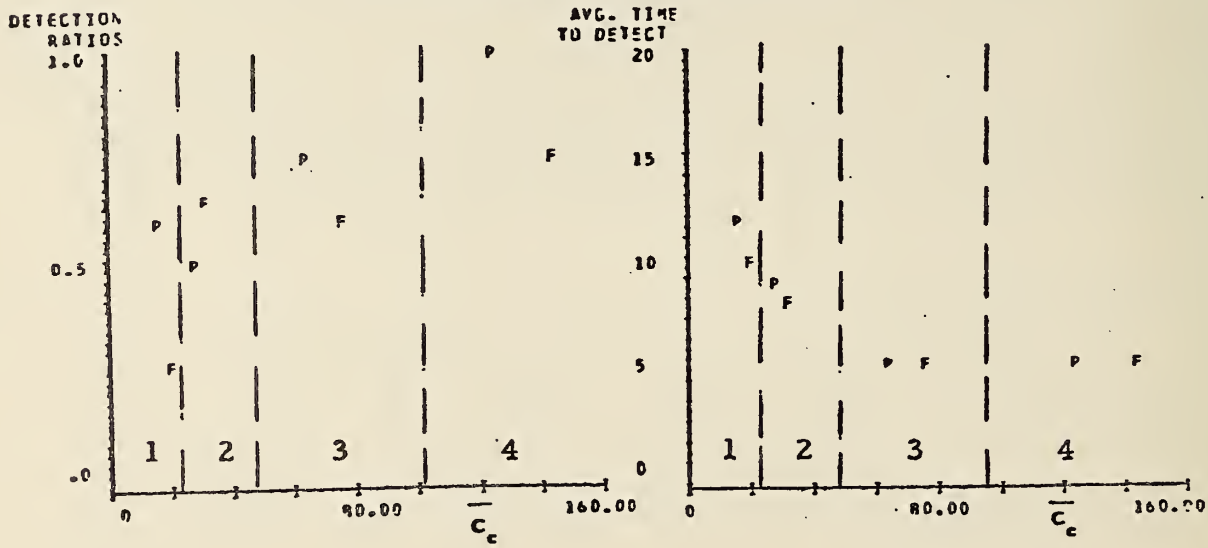
The alignment simulations involved a level to a 3 percent grade, a level to a 6 percent grade, and a straight section to a curve of radius 2000 feet (610 M). The high traffic volume results are obtained by averaging results for total volumes of 4200 and 4800 vehicles per hour, while the low volume results are obtained by averaging results for total volumes of 3000 and 3600 vehicles per hour.

3 Percent Grade

Figures 33 and 34 present the results for the 3 percent grade case. For spacings of 500 and 1000 feet (152 and 305 M), the detection ratios and detection times are comparable for both station configurations. Increasing the spacing to 2500 feet (762 M) results in decreases in detection ratio and increases in detection time. Because of the effectiveness degradation at 2500 foot (762 M) spacings and the comparable performance of the full and partial configurations, the 1000 foot (305 M) partial configuration is the most cost effective choice.



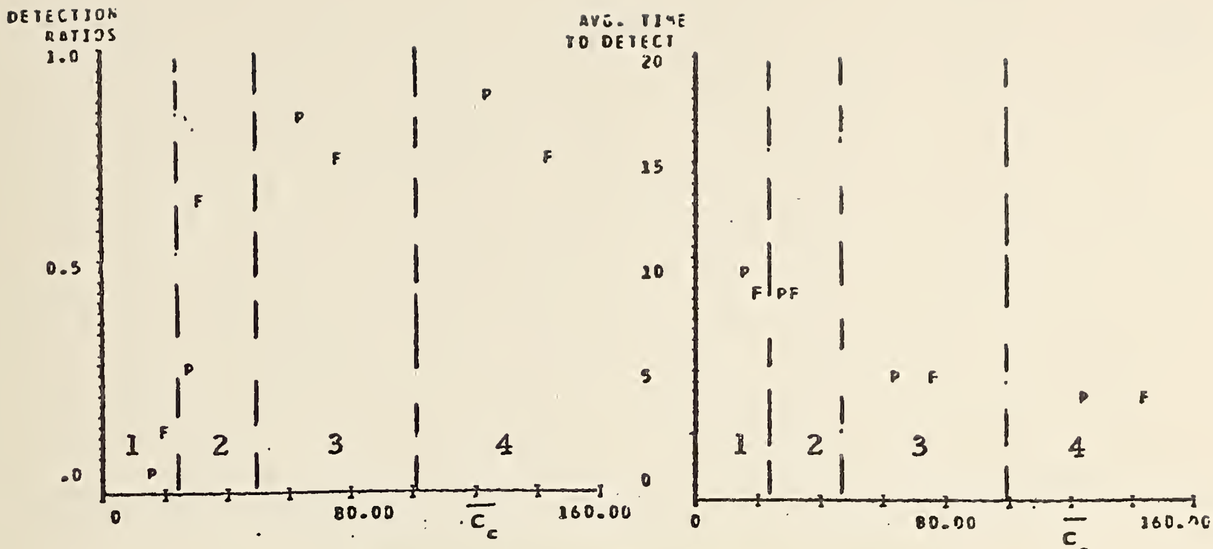
a) Averaged over all volumes



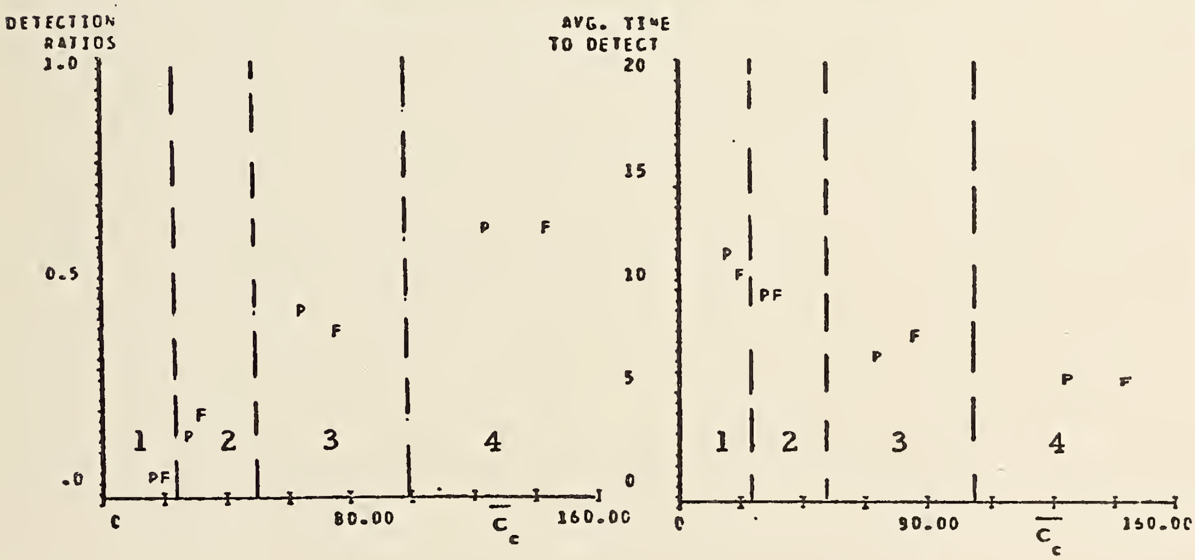
b) High total volume (5400 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 31 COST EFFECTIVENESS PLOTS FOR LANE DROP SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



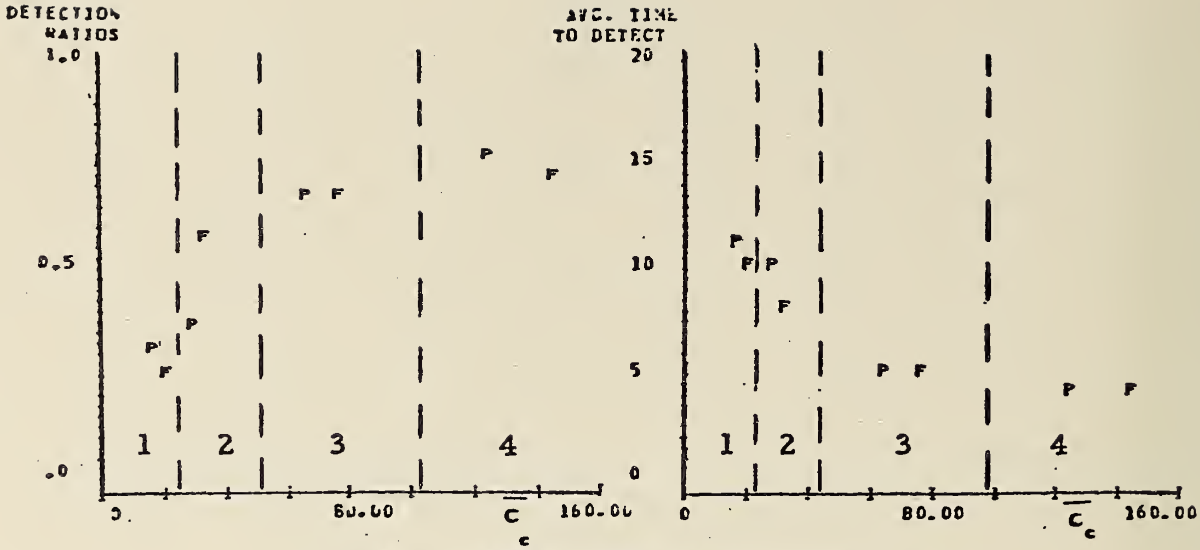
c) Medium total volume (4500 veh/hr)



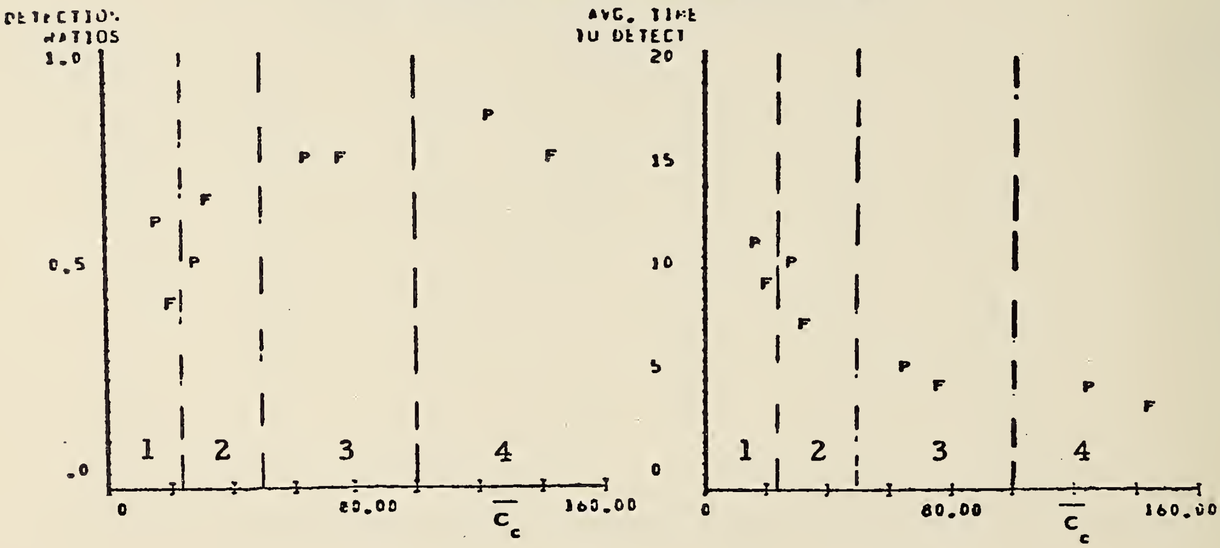
d) Low total volume (3000 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 31 CONTINUED



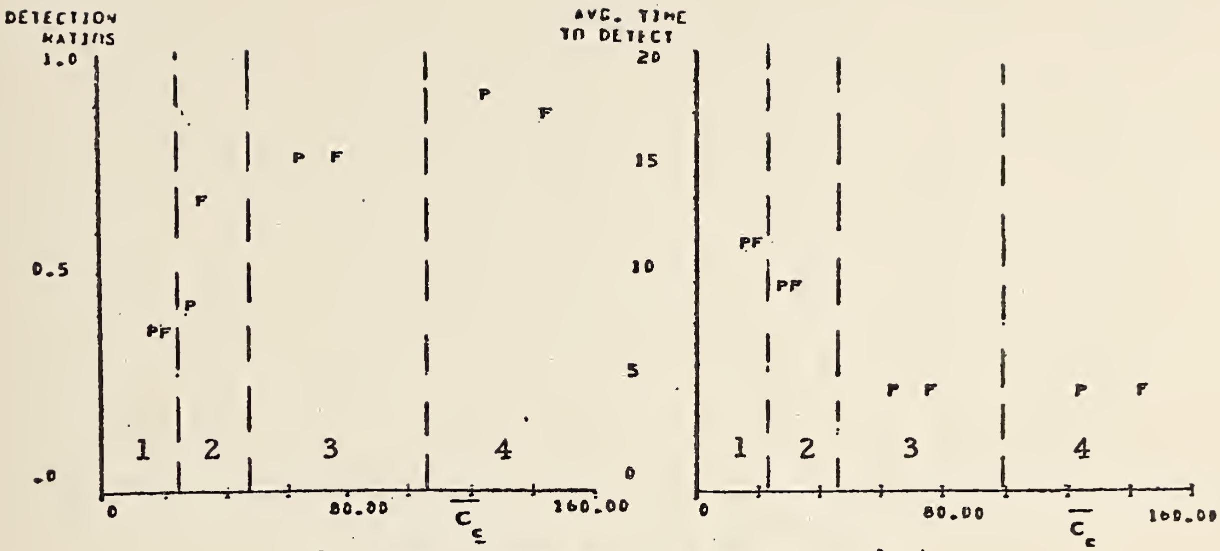
a) Averaged over all volumes



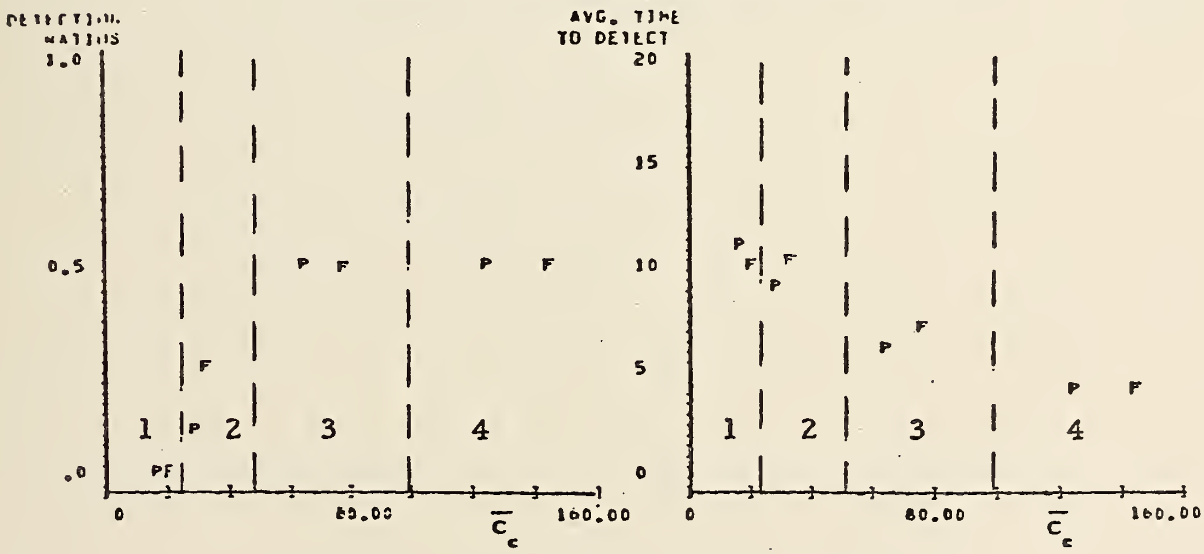
b) High total volume (5400 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 32 COST EFFECTIVENESS PLOTS FOR LANE DROP SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



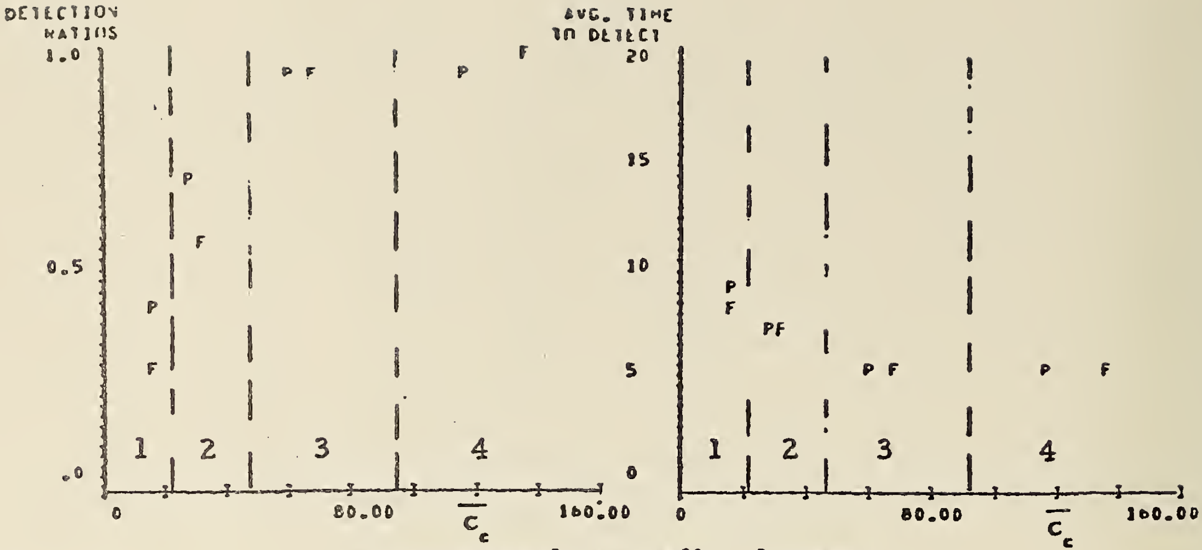
c) Medium total volume (4500 veh/hr)



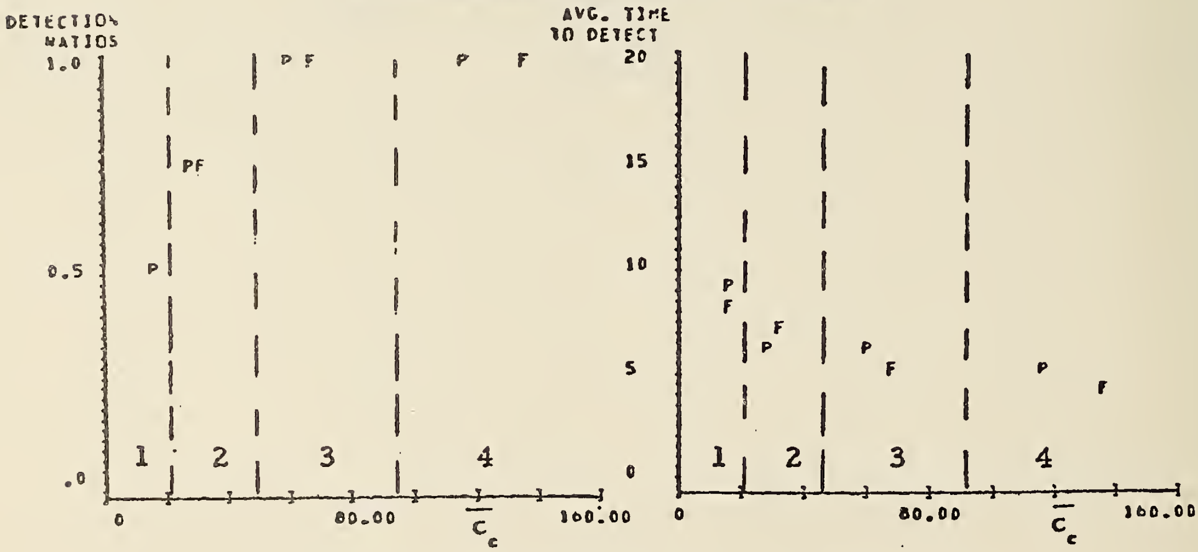
d) Low total volume (3000 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 32 CONTINUED



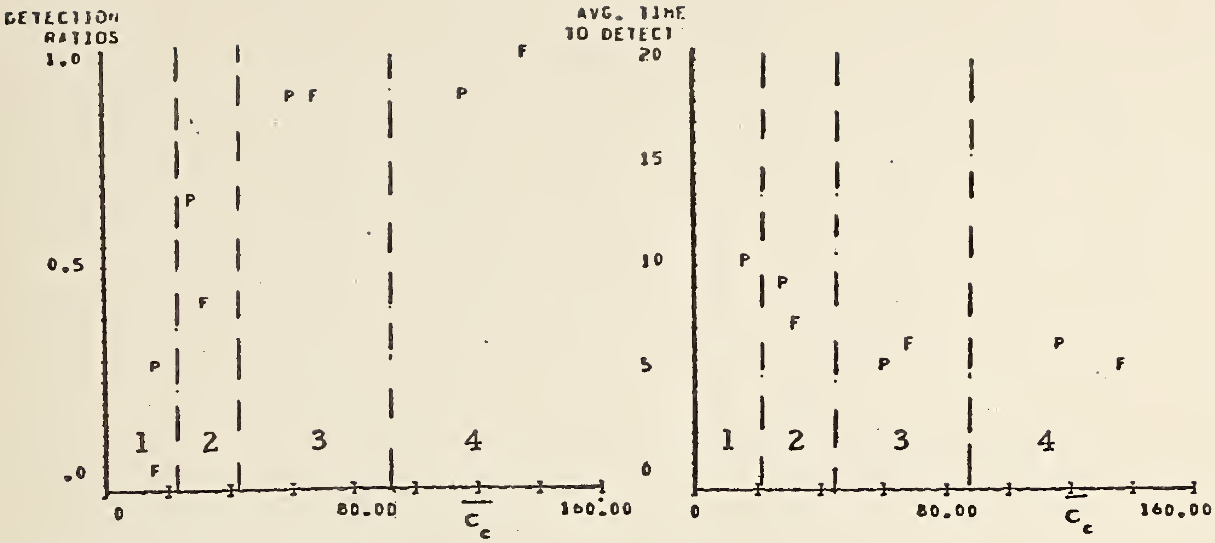
a) Averaged over all volumes



b) High total volume (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

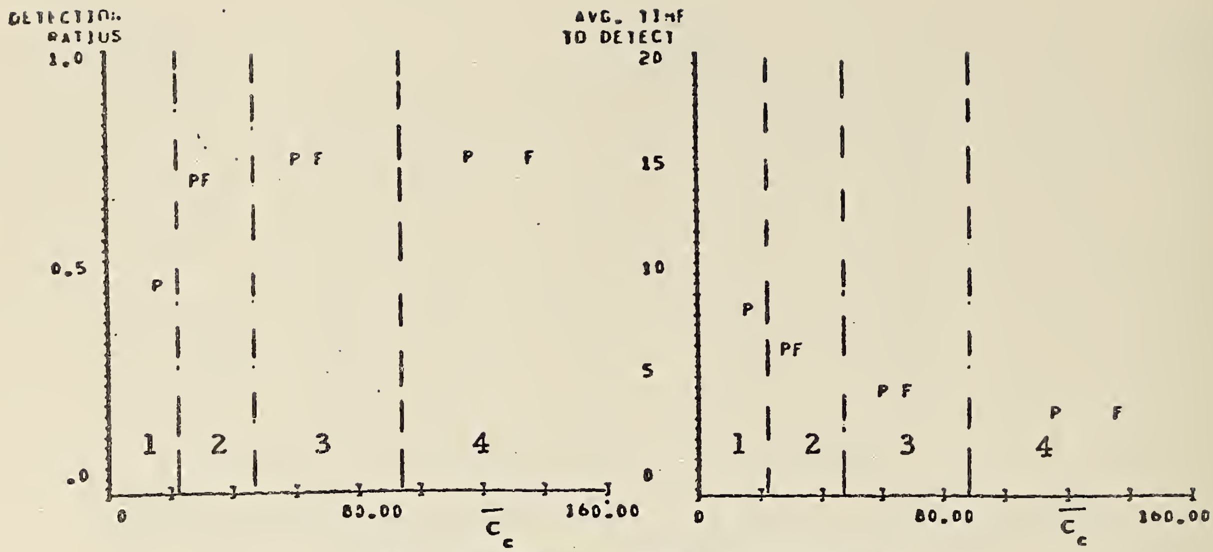
FIGURE 33 COST EFFECTIVENESS PLOTS FOR 3 PERCENT GRADE ALIGNMENT SIMULATIONS WITH MODIFIED CALIFORNIA ALGORITHM



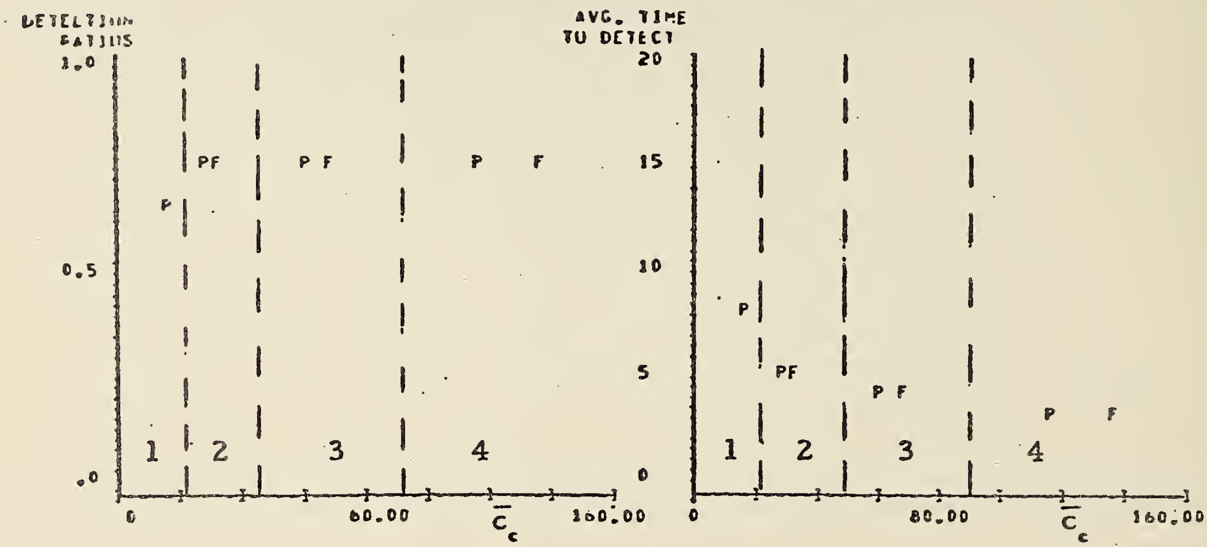
c) Low total volume (3000 and 3600 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 33 CONTINUED



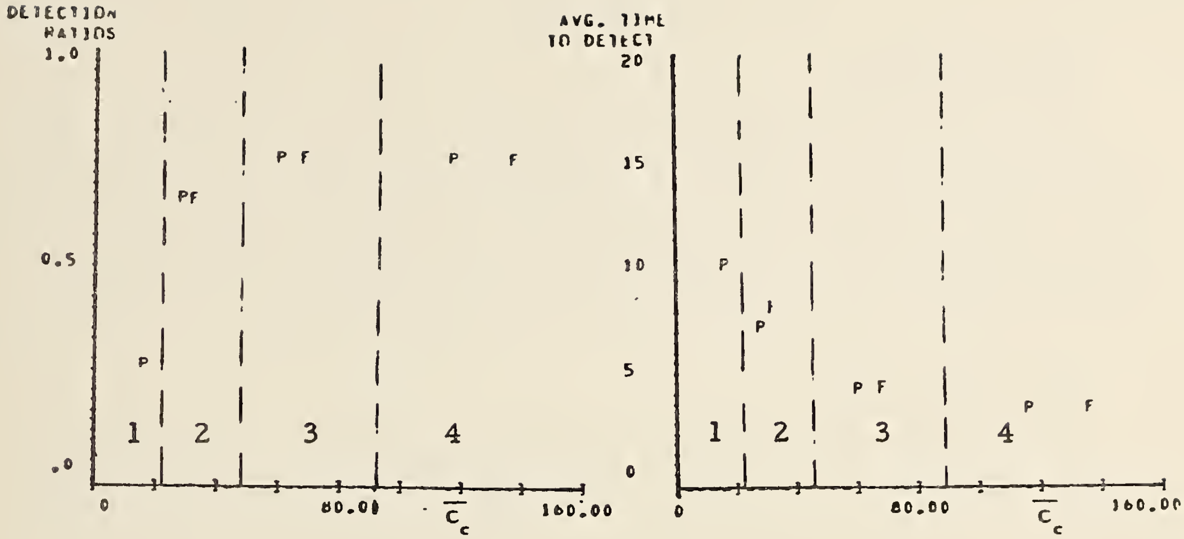
a) Averaged over all volumes



b) High total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 34 COST EFFECTIVENESS PLOTS FOR 3 PERCENT GRADE ALIGNMENT SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



c) Low total volumes (3000 and 3600 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 34 CONTINUED

6 Percent Grade

The results for this case are presented in Figures 35 and 36. The results are similar to the 3 percent grade case except that the degradation in effectiveness in going to a 2500 foot (762 M) spacing is much less severe. For this reason, the partial configuration with a spacing between 1000 and 2500 feet (305 and 762 M), depending on the needs and budget of the user, represents a reasonable choice.

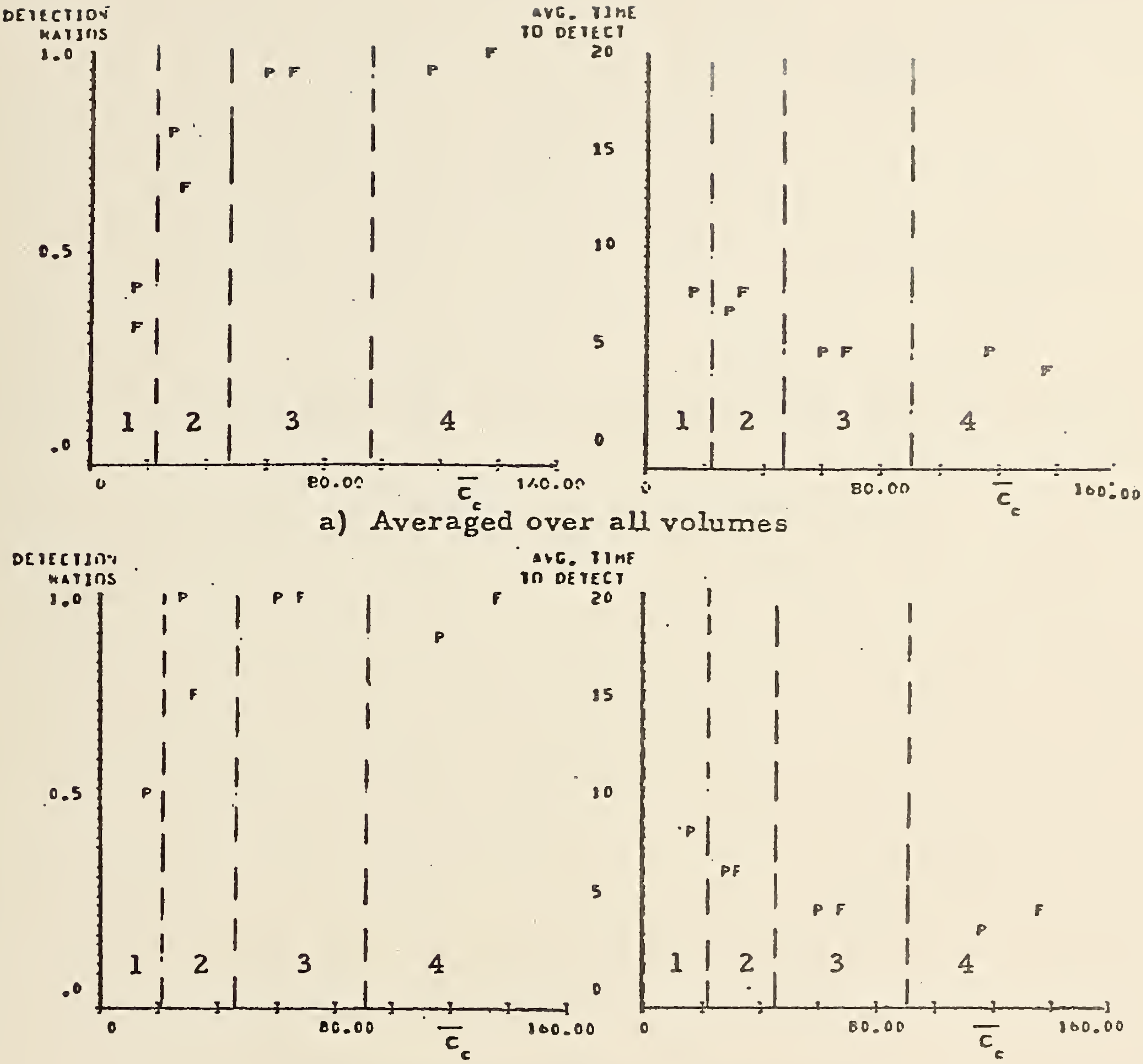
Curve Alignment

The cost effectiveness plots for these simulations are presented in Figures 37 and 38. The detection ratios for configurations of 500, 1000, and 2500 feet (152, 305 and 762 M) spacings are all comparable, except for the 2500 foot (762 M) full configuration using the Modified California detection algorithm. The detection times for the 500 and 1000 foot (152 and 305 M) spacings are comparable, but these times increase when the spacing is increased to 2500 feet (762 M). Because of the comparable effectiveness of the two configurations, the most cost effective sensor placement is attained by a partial lane configuration with a spacing from 1000 to 2500 feet (305 to 762 M) depending on the needs and budget of the user.

4.3 SUMMARY OF CONCLUSIONS ON COST EFFECTIVENESS ANALYSIS

Table 30 summarizes the results of the cost effectiveness analyses discussed in Section 4.2. In general, a partial lane configuration performs about as well as a full configuration. Therefore, from a cost effectiveness viewpoint, the partial configuration is preferred.

Sensor spacings greater than 2500 feet (762 M) generally result in poor detection ratios and times. In contrast, the effectiveness measures for 500 and 1000 foot (152 and 305 M) spacings are very close. Therefore, the most cost effective sensor spacings usually fall into the range from 1000 to 2500 feet (152 to 305 M). The only exception to this conclusion occurs in lane drop situations, where a spacing less than 1000 feet (305 M) appears to be more cost effective.

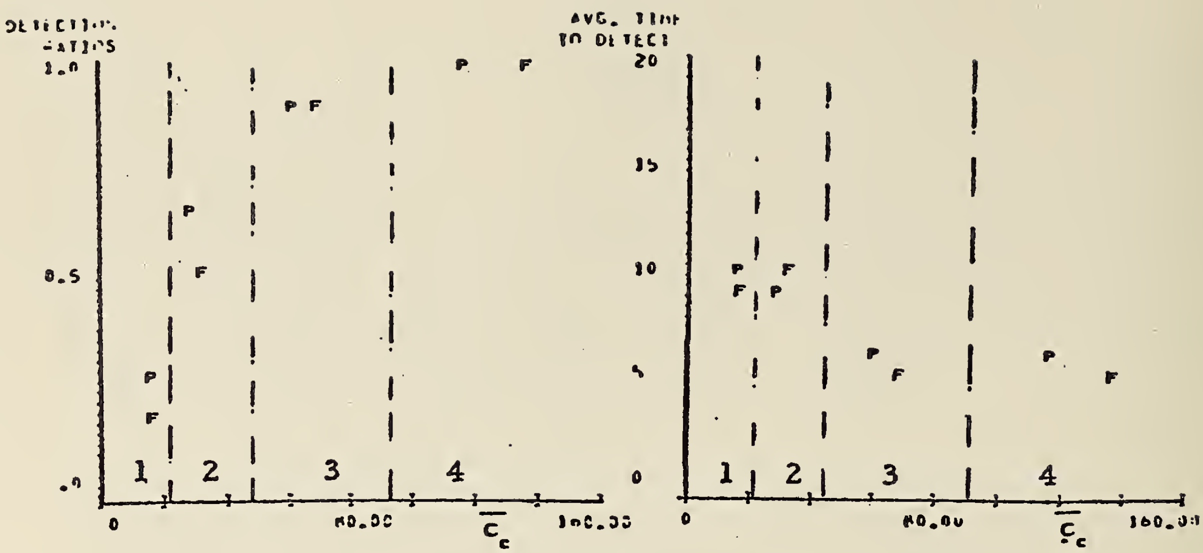


a) Averaged over all volumes

b) High total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

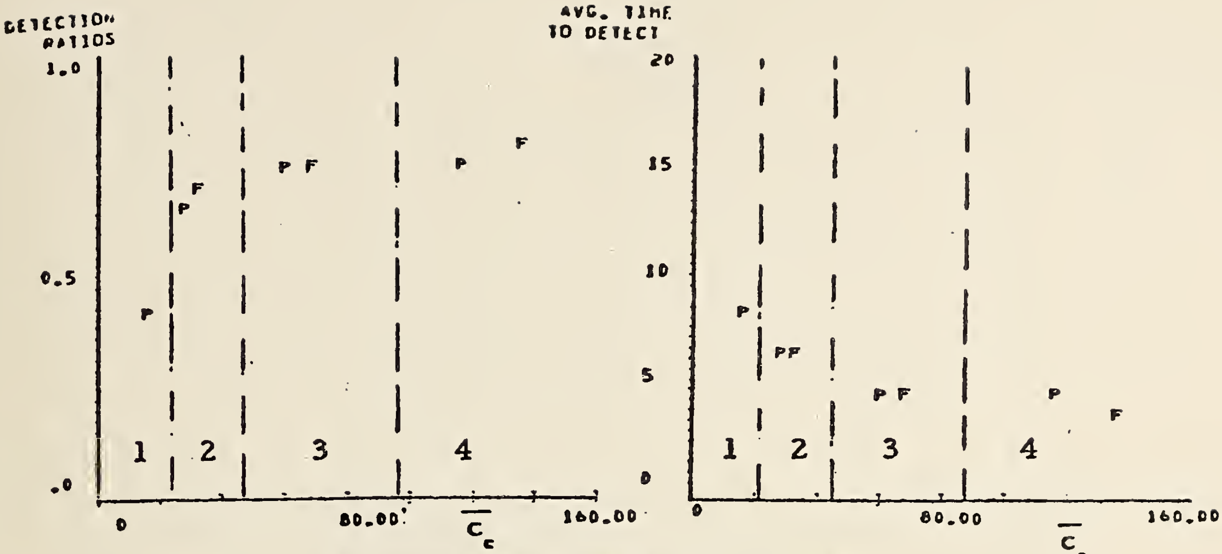
FIGURE 35 COST EFFECTIVENESS PLOTS FOR 6 PERCENT GRADE ALIGNMENT SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



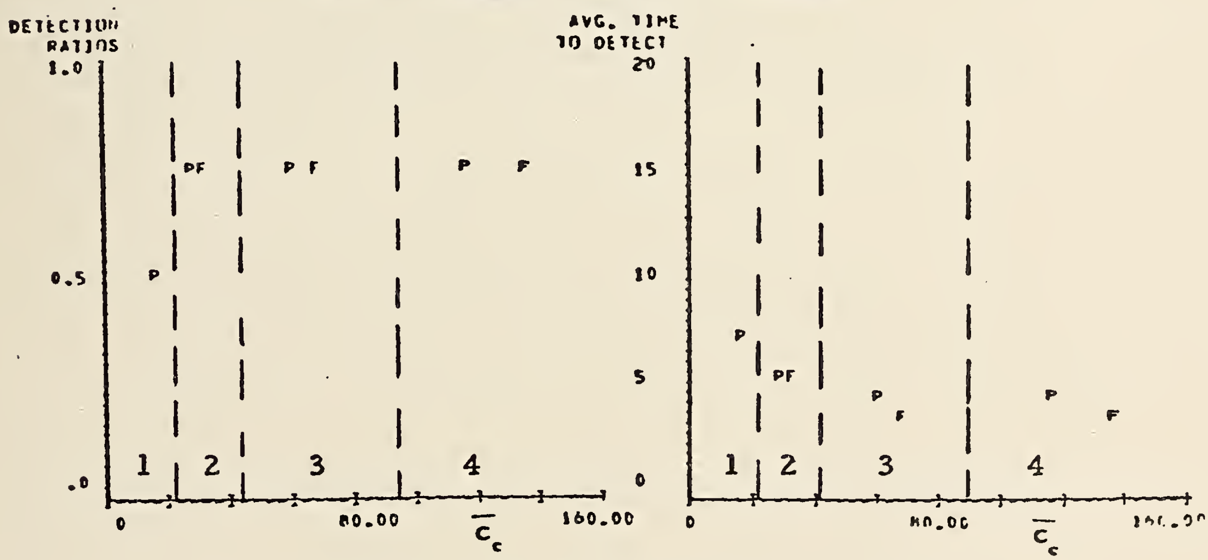
c) Low total volumes (3000 and 3600 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 35 CONTINUED



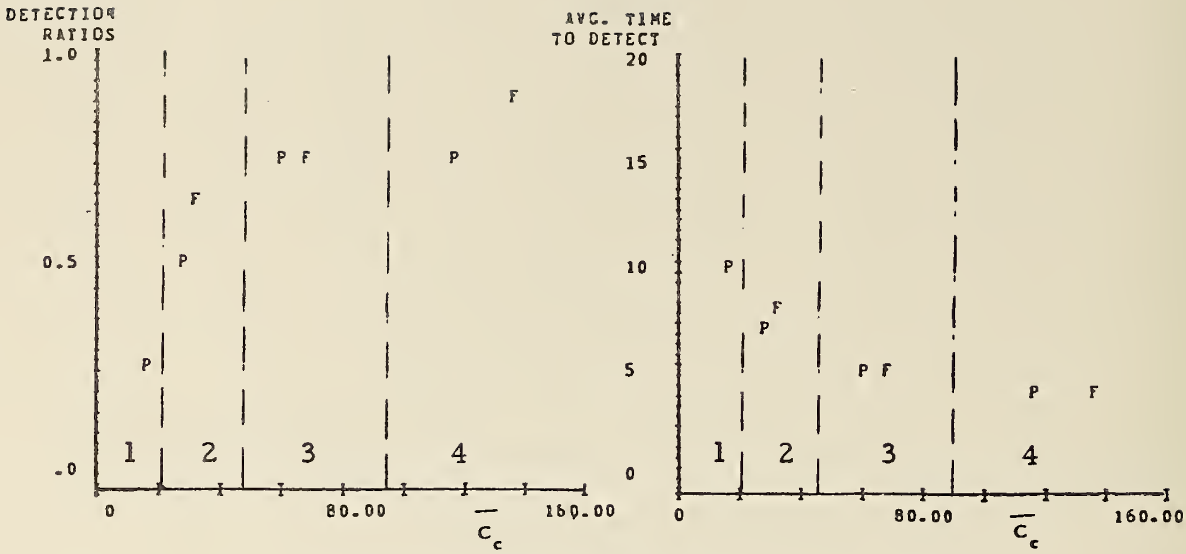
a) Averaged over all volumes



b) High total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

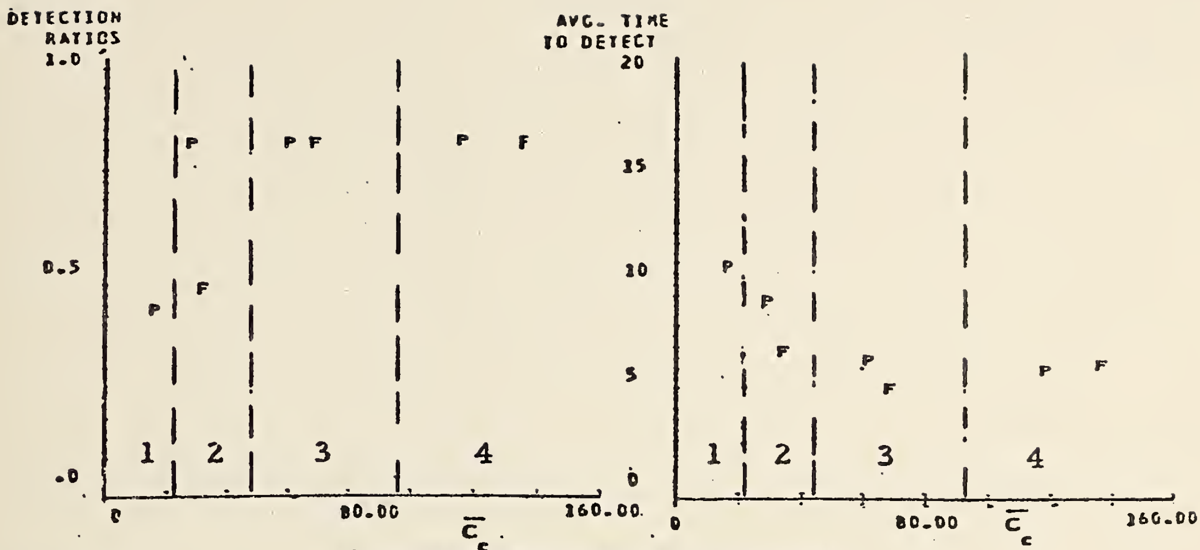
FIGURE 36 COST EFFECTIVENESS PLOTS FOR 6 PERCENT GRADE ALIGNMENT WITH PAYNE NUMBER 7 DETECTION ALGORITHM



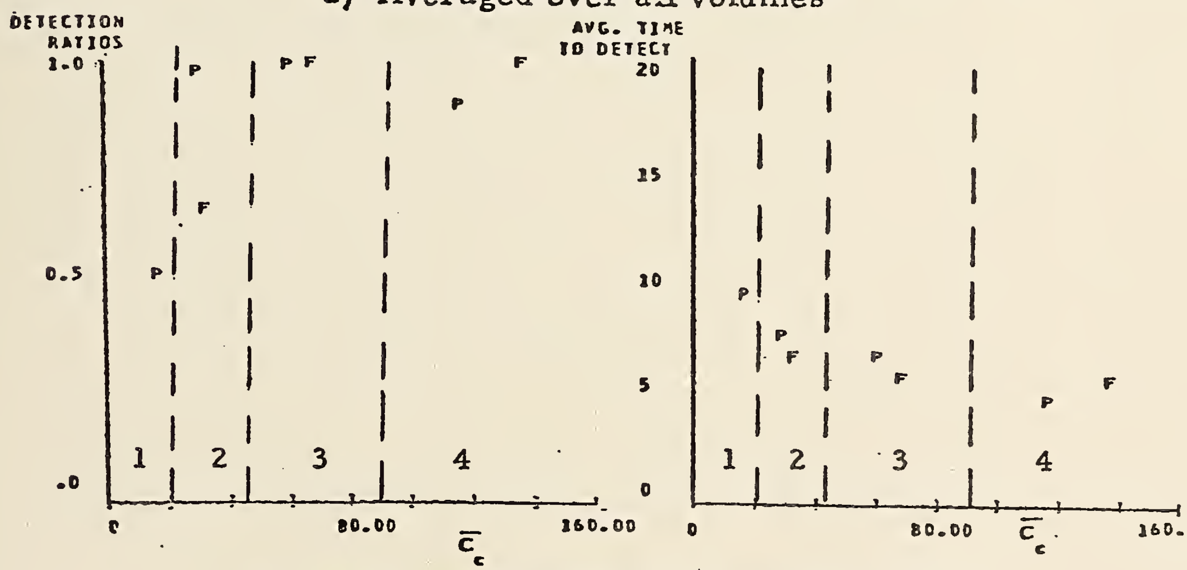
c) Low total volumes (3000 and 3600 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 36 CONTINUED



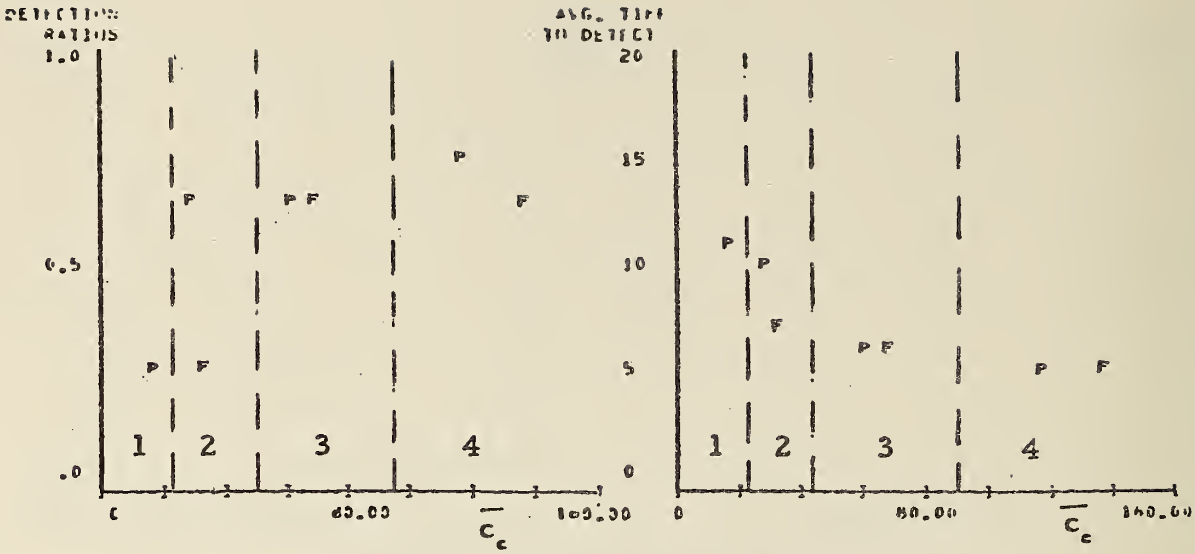
a) Averaged over all volumes



b) High total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

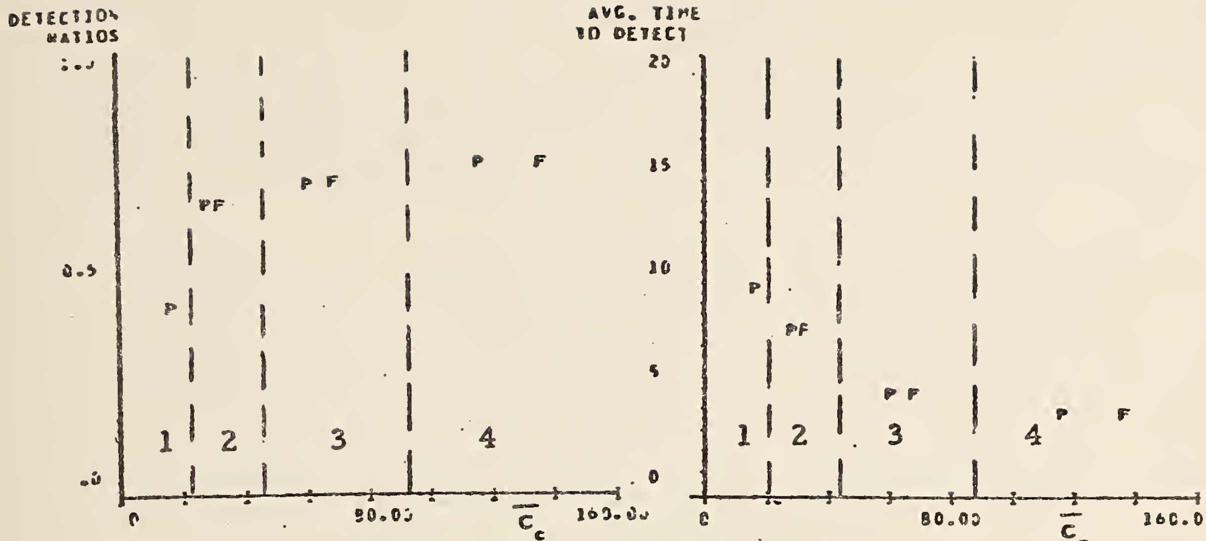
FIGURE 37 COST EFFECTIVENESS PLOTS FOR CURVE ALIGNMENT SIMULATIONS WITH MODIFIED CALIFORNIA DETECTION ALGORITHM



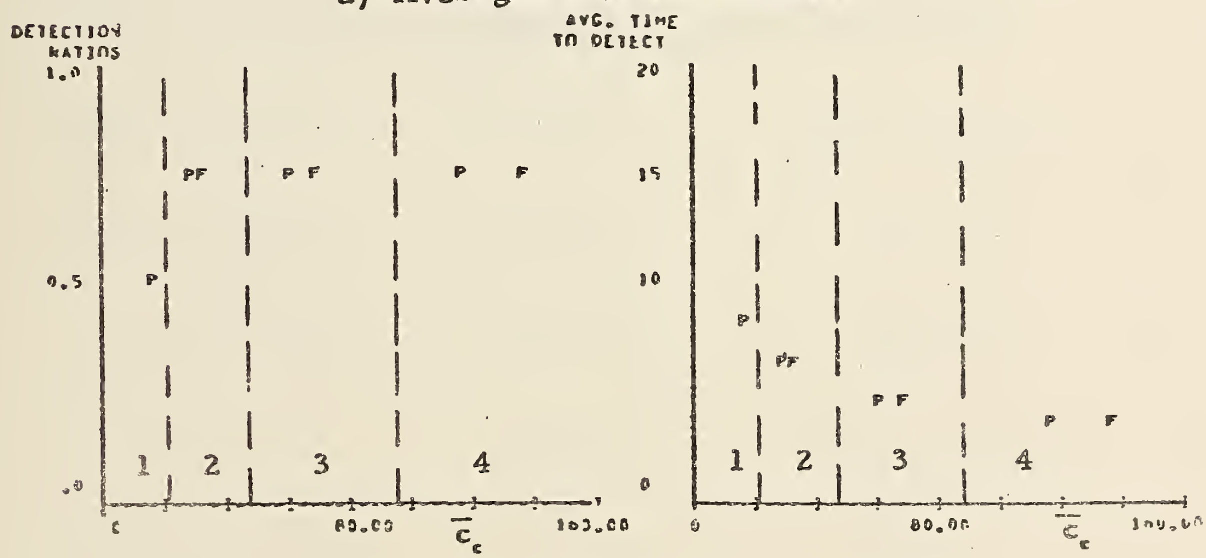
c) Low total volumes (3000 and 3600 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 37 CONTINUED



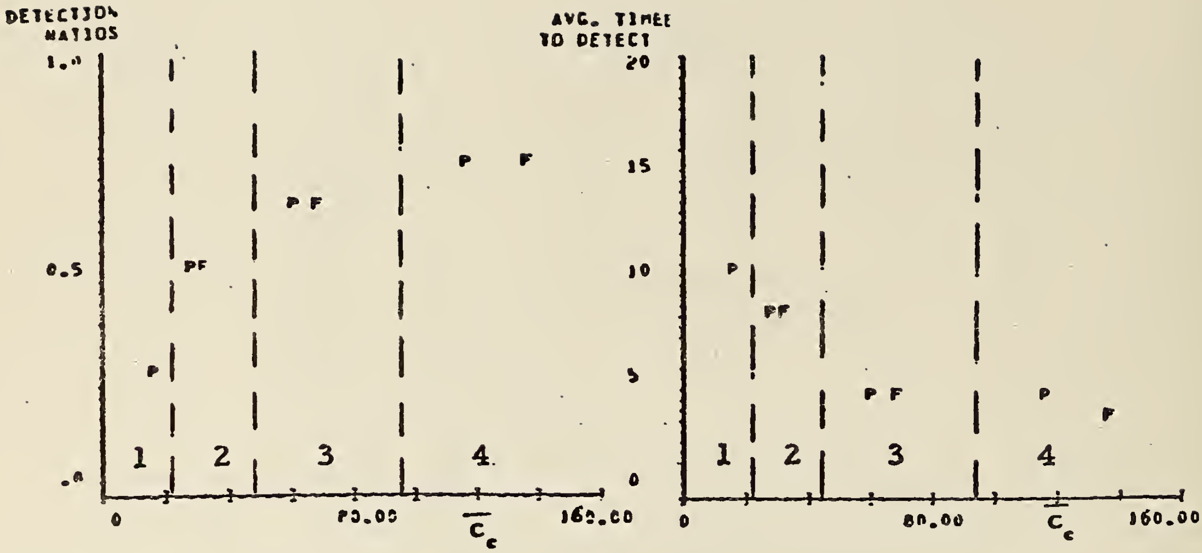
a) Averaged over all volumes



b) High total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 38 COST EFFECTIVENESS PLOTS FOR CURVE ALIGNMENT SIMULATIONS WITH PAYNE NUMBER 7 DETECTION ALGORITHM



c) Low total volumes (4200 and 4800 veh/hr)

1 = 5000 ft. (1524 M)
2 = 2500 ft. (762 M)
3 = 1000 ft. (305 M)
4 = 500 ft. (152 M)

FIGURE 38 CONTINUED

TABLE 30 SUMMARY OF COST EFFECTIVENESS SENSOR PLACEMENTS

Situation	Sensor Configuration	Sensor Spacing
Mainline 3 lanes	Partial	1000 to 2500 feet (305 to 762 M)
Mainline 4 lanes	Partial	1000 to 2500 feet (305 to 762 M)
Weaving 1000 feet (305 M)	Depends on Detection Algorithm	1000 feet (305 M)
Weaving 2000 feet (610 M)	Partial	1000 to 2500 feet (305 to 762 M)
Weaving 3000 feet (914 M)	Partial	2500 feet (762 M)
Lane Additions	Partial	1000 feet (305 M)
Lane Drops	Partial	500 to 1000 feet (152 to 305 M)
3 Percent Grade Alignment	Partial	1000 feet (305 M)
6 Percent Grade Alignment	Partial	1000 to 2500 feet (305 to 762 M)
Curve Alignment	Partial	1000 to 2500 feet (305 to 762 M)

CHAPTER 5

SUMMARY OF GUIDELINES FOR SENSOR PLACEMENT

The results from the analyses presented in the previous two chapters will be summarized in the form of guidelines that should assist using agencies in determining the best lane instrumentation at a given station and sensor spacings based on incident detection performance requirements and budget. First general guidelines that are valid for any of the four freeway geometries studied herein are given. Then, specific guidelines for individual geometric design features will be indicated.

5.1 GENERAL GUIDELINES

General guidelines can be specified for the sensor configuration at a given station and for the spacing between stations.

Station Configurations: Results for all the geometric freeway conditions considered clearly indicate that the effectiveness measures of detection ratio and detection time for partial sensor configurations are comparable to those for full sensor configurations for a given spacing between stations. Because of their lower cost, the partial configurations are universally the most cost effective choice based on these effectiveness measures. There is, however, the issue of reliability of the sensor configurations, an effectiveness measure which was not considered in this study. Reliability considerations could dictate the use of full sensor configurations despite their slightly increased cost compared to partial configurations. This reliability-cost issue needs to be addressed in a future study.

Station Spacing: All results indicate that station spacings over 2500 feet (762 M) produce unsatisfactory incident detection algorithm performance. In contrast, decreasing the spacing below 1000 feet (305 M) generally produces relatively little or no increase in effectiveness, while increasing the cost. Between spacings of 1000 and 2500 feet (305 and 762 M) there is a cost effectiveness tradeoff that varies among the four types of geometric freeway sections. The costing procedures described in Chapter 4 can be used to determine the most cost effective station spacing between 1000 and 2500 feet (305 and 762 M) based on the user's requirements and budget.

5.2 MAINLINE FREEWAY SECTIONS

The general guidelines summarized above are valid for mainline freeway sections. Specific comments can be made for false alarm rates and the placement of sensors relative to on and off ramps.

False Alarm Rates: The results show that the false alarm rates increase when the station spacing is reduced to 500 feet (152 M). This further reinforces the recommended minimum station spacing of 1000 feet (305 M).

Effect of On and Off Ramps: There is evidence that it is advantageous to locate sensor stations upstream of on ramps and downstream of off ramps. This conclusion is tentative and requires further study.

5.3 WEAVING FREEWAY SECTIONS

The general guidelines are valid for weaving sections. The cost effectiveness analysis of Chapter 4 indicates that in the recommended range of sensor spacings between 1000 and 2500 feet (305 and 762 M) values to the lower end are most cost effective for short weaving sections, e.g., 1000 feet (305 M). In contrast, for long weaving sections, e.g., 3000 feet (914 M) station spacings closer to 2500 feet (762 M) appear to be most cost effective.

5.4 LANE ADDITIONS AND DROPS

The general guidelines are valid for freeway sections with lane additions and lane drops. The recommended lower station spacing limit of 1000 feet (305 M) is reinforced by the increased false alarm rate evident with a spacing of 500 feet (152 M) in the lane addition case.

5.5 ALIGNMENT FREEWAY SECTIONS

The general guidelines are valid without modification for pipeline freeway sections in which there is a change in alignment.

APPENDIX

FIM TECHNIQUES AND EXTENDED INCIDENT SCENARIOS

The evaluations of candidate sensor configurations performed in this study were based upon three measures of incident detection algorithm effectiveness—time to detect, detection ratio, and false alarm rate. In the experimental program design and implementation phase, consideration was given to an additional measure of effectiveness parameter—delay. More precisely, this is the incremental delay, in minutes, incurred by vehicles as a result of the incident. Such delay is incurred until normal flow is resumed.

Delay is a measure which must be derived analytically. Techniques for doing so are discussed by Owen and Urbanek (1) in their work on Freeway Incident Management (FIM). Moreover, their techniques permit an extension to the number of incident scenarios which may be studied.

For reasons to be briefly described in this Appendix, delay was not utilized in the evaluation phases of this study. However, for completeness of presentation, this Appendix will first address the general FIM analysis techniques for computing delay, provide a definition of the extended incident scenarios which were considered, and show the calculation of delay for these scenarios.

1.1 COMPUTATION OF DELAY

The delay caused by freeway incidents can be represented graphically in terms of traffic flow rates as shown in Figure 39. The horizontal axis is a time line indicating the occurrence of certain incident-related events. It is used to measure the overall duration of incident-caused impacts on traffic flow. The vertical axis is the cumulative traffic volume, i.e., the total sum of the vehicles having passed any given point on the freeway in a defined time period.

The total number of vehicles desiring to use the freeway, the demand flow rate, can be represented by the line, S2. When an incident occurs (time A), the traffic flow decreases below the demand flow due to a lane blockage or the formation of gaper blocks. This reduced volume (shown as line S3 in Figure 39) remains in effect until the incident is cleared from

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[1] J. R. Owen and G. L. Urbanek, Ibid.

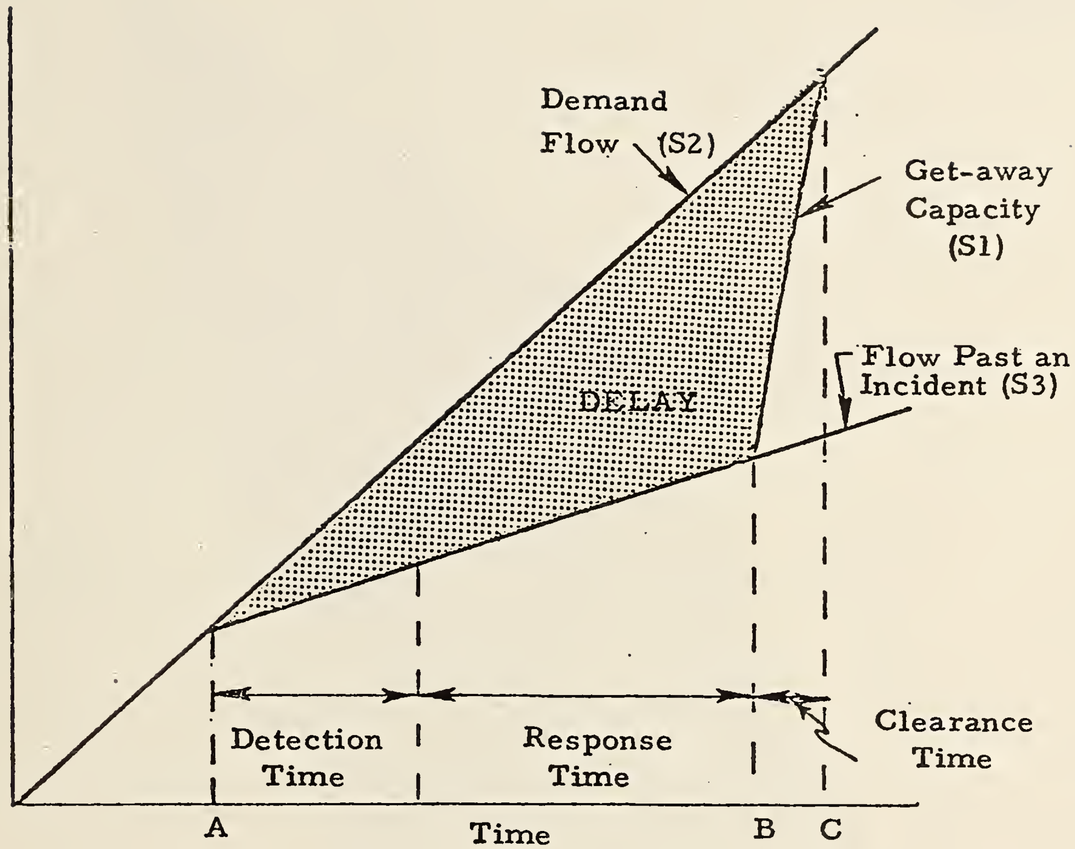

FIGURE 39 EVENTS FOLLOWING AN INCIDENT

the freeway (time B). At that time, the queued traffic can begin flowing at a "get-away" rate approaching the freeway's capacity (S1). At time C, the last vehicle in the queue reaches the normal flow speed, and the traffic resumes flowing at the demand rate. The area bounded by the lines S1, S2, and S3 represents the total amount of delay (in vehicle-minutes) created by the incident. The amount of time from A to C is the time to normal flow.

Using this representation, the total delay incurred and the time to normal flow may be computed algebraically for a variety of incident scenarios. The delay and time to normal flow equations were developed by Owen for the most general scenario which is illustrated in Figure 40. For this figure, the following notation applies:

S_1 - capacity flow rate of the facility, vehicles/minute

S_2 - initial demand flow rate, vehicles/minute

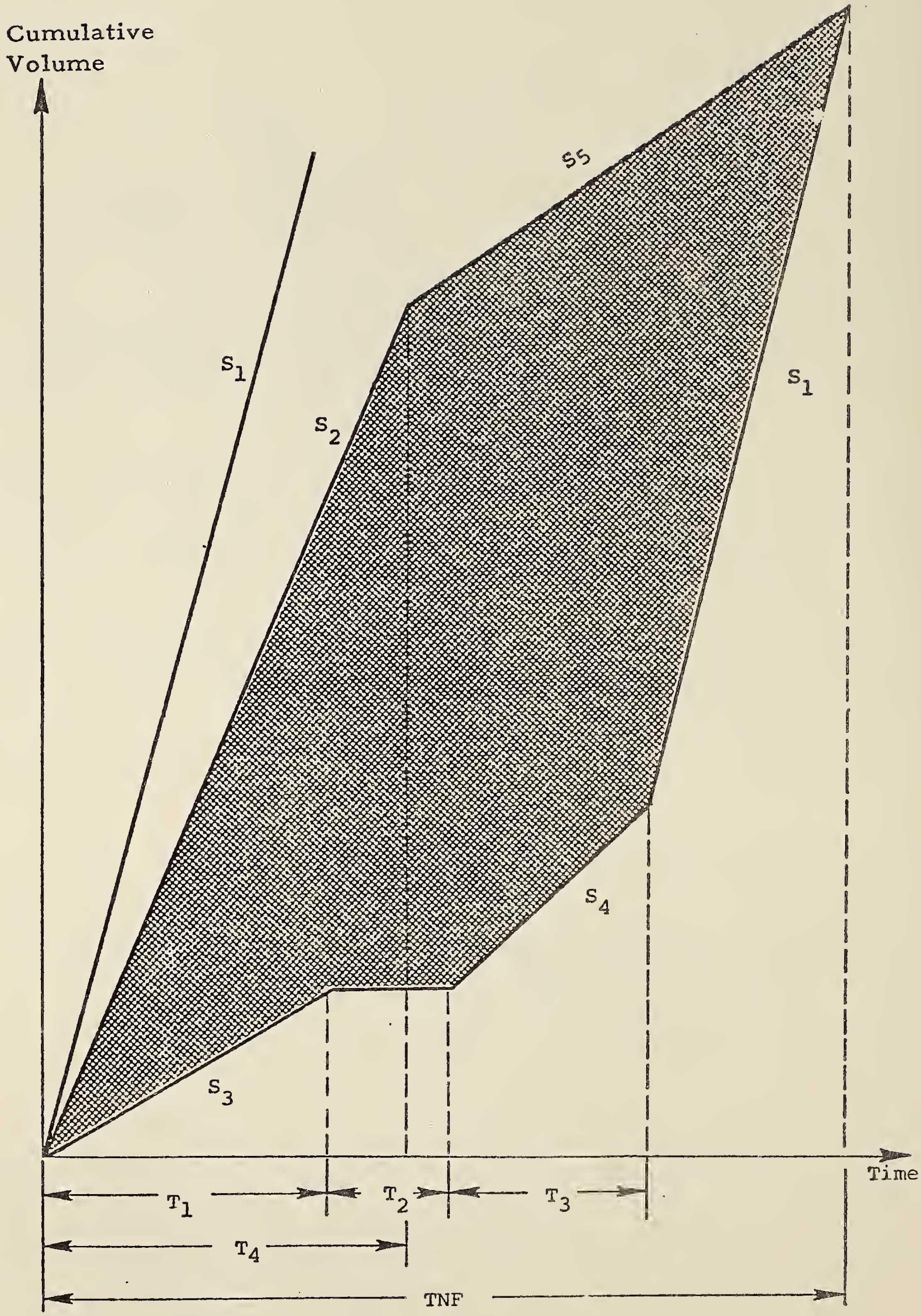

FIGURE 40 GENERAL DELAY CONDITION

S_3 - initial bottleneck flow rate, vehicles/minute

S_4 - adjusted bottleneck flow rate, vehicles/minute

S_5 - revised demand flow rate, vehicles/minute

T_1 - incident duration until first change, minutes

T_2 - duration of total closure, minutes

T_3 - incident duration under adjusted flow, minutes

T_4 - elapsed time under initial demand, minutes

D - total delay, vehicle-minutes

TNF - total elapsed time until normal flow is resumed, minutes

The equation for computing delay for the general condition is:

$$
\begin{aligned}
D = \Big[& T_1^2 (S_1 - S_3)(S_5 - S_3) + T_2^2 S_1 S_5 + T_3^2 (S_1 - S_4)(S_5 - S_4) \\
& - T_4^2 (S_1 - S_2)(S_2 - S_5) + 2T_1 T_2 S_1 (S_5 - S_3) \\
& + 2T_1 T_3 (S_1 - S_4)(S_5 - S_3) + 2T_1 T_4 (S_1 - S_3)(S_2 - S_5) \\
& + 2T_2 T_3 S_5 (S_1 - S_4) + 2T_2 T_4 S_1 (S_2 - S_5) \\
& + 2T_3 T_4 (S_1 - S_4)(S_2 - S_5) \Big] \Big/ 2 (S_1 - S_5) .
\end{aligned}
\tag{8}
$$

Similarly, an expression for the time until normal flow is resumed can be computed as:

$$
TNF = \frac{T_1 (S_1 - S_3) + T_2 S_1 + T_3 (S_1 - S_4) + T_4 (S_2 - S_5)}{(S_1 - S_5)} \tag{9}
$$

1.2 EXTENDED INCIDENT SCENARIOS

In Chapter 2, it was pointed out that the INCES module analysis of each sensor actuation data file produced the three critical flow rates, arrival demand, discharge capacity, and get-away flow. Referring to Figure 39, these rates are precisely S2, S3, and S1. Furthermore, by applying incident detection algorithms, data on detection time was also computed for each simulation run/candidate sensor configuration combination. Consequently, the INCES module output data can be used to algebraically compute the effectiveness measure delay under a variety of additional incident scenarios.

A total of ten extended incident scenarios were designed for further study:

(1) A self-repairing, short duration incident. Two durations were used, five and ten minutes (Scenarios 1, 2).

(2) A gross representation of the effects of ramp control. At the time the incident is detected, the arrival demand is reduced and the incident is cleared a fixed time later. Parameters which are varied are:

Demand reduction - 0% (no control)
20% (approximation to ramp control)

Fixed clearance time - 10 minutes
15 minutes

Permutations of these parameters correspond to Scenarios 3 through 6.

(3) A gross representation of ramp control coupled with the response to the scene impeded by congestion. In this set of scenarios, the incident duration is a function of the arrival demand, bottleneck capacity and a fixed response time. As in the type 2 case, the parameters considered are:

Demand reduction - 0% (no control)
20% (approximation to ramp control)

Fixed response time - 10 minutes
15 minutes

Permutations of the type 3 parameters represent Scenarios 7 through 10.

1.3 DELAY AND TIME TO NORMAL FLOW FOR THE EXTENDED INCIDENT SCENARIOS

Using Equations 8 and 9, it is possible to derive expressions for delay and time to normal flow (TNF) for each extended incident scenario.

Type 1: Self-repairing, short duration incident. Referring to Figure 40, it can be seen that the conditions for this incident type are:

$$S_5 = S_2$$

$$T_2 = T_3 = 0$$

Substituting these conditions into Equations 8 and 9 yields:

$$\text{Delay} = T_1^2 \frac{(S_1 - S_3)(S_2 - S_3)}{2(S_1 - S_2)} \tag{10}$$

$$\text{TNF} = \frac{T_1(S_1 - S_3)}{(S_1 - S_2)} \tag{11}$$

Type 2: A gross representation of the effects of ramp control. At the time the incident is detected, the arrival demand is reduced and the incident is cleared a fixed time later. The conditions for this incident type are:

$$T_4 = \text{time to detect}$$

at time T_4, $S_5 = (1 - \alpha)S_2$ where α is the percent reduction in demand.

$$T_1 = T_4 + A$$

$$T_2 = T_3 = 0$$

Substituting in (8) and (9)

$$\text{Delay} = \frac{(S_1 - S_3)(S_5 - S_3)T_1^2 + 2T_4(S_1 - S_3)(S_2 - S_5)T_1 - T_4^2(S_1 - S_2)(S_2 - S_5)}{2(S_1 - S_5)} \tag{12}$$

$$\text{TNF} = \frac{T_1(S_1 - S_3) + T_4(S_2 - S_5)}{(S_1 - S_5)} \tag{13}$$

Type 3: A gross representation of ramp control coupled with the situation where the response to the scene is impeded by congestion. In this set of scenarios, the incident duration is a function of the arrival demand, bottleneck capacity and a fixed response time. After T_4 seconds (the time the incident is detected), the upstream demand is reduced and the response team joins the queue. The time it takes the response team to work its way through the queue is given by

$$\frac{(S_2 - S_3)T_4}{S_3}$$

where S_2 = arrival demand, S_3 = bottleneck capacity, and T_4 = elapsed time between incident initiation and detection.

$$T_1 = T_4 + \left(\frac{S_2 - S_3}{S_3}\right) T_4 + A$$

or

$$T_1 = \left(\frac{S_2}{S_3}\right) T_4 + A$$

where A is a fixed time. Again, as for the type 2 incident,

$$S_5 = (1 - \alpha) S_2$$

$$T_2 = T_3 = 0$$

Substituting in Equations 8 and 9 again yields Equations 12 and 13 for this type of incident.

1.4 EXCLUSION OF DELAY FROM THE EVALUATION PROCESS

Delay calculations were, in fact, performed for each extended incident scenario/candidate sensor configuration/incident detection algorithm/INTRAS simulation combination. However, these calculations were not used in studying the problem of optimum sensor placement. An explanation follows. For given physical configuration, traffic volume and incident severity, this delay measure is a function of the detection ratio, time to detect and the extended incident scenario. Because of the dependence on the extended incident scenario, which is not a function of sensor placement, the delay measure does not provide as direct a measure of effectiveness as do the detection ratio and time to detect. Two other problems also occur when this FIM calculated delay is used as an effectiveness measure. First, detection must occur for this measure to have validity. Thus this measure is often not available under relatively light traffic flow and minor incident situations wherein the incident detection ratio tends to be low. Second, due to the structure of the FIM calculations, negative values of delay result for cases in which the vehicle arrival demand exceeds the get-away flow and when this arrival demand is less than the discharge capacity, as can be seen from the equations used in the FIM calculations. Since a negative value of delay is meaningless as an effectiveness measure, any such results would have to be discarded in a cost-effectiveness evaluation.

☆U.S. GOVERNMENT PRINTING OFFICE: 1980 620-678/764 1-3

FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.

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